VOLUME 103 PART A NUMBER 7 FEBRUARY 1956

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

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PART A

POWER ENGINEERING

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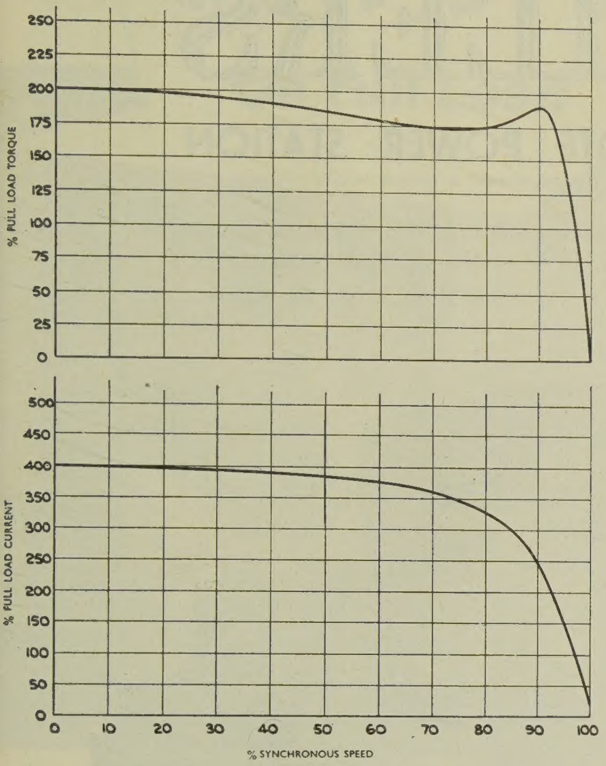

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A Trislot motor can be used in circumstances for which a normal squirrel-cage motor would be unsuitable by reason of excessive starting current and/or insufficient starting torque.

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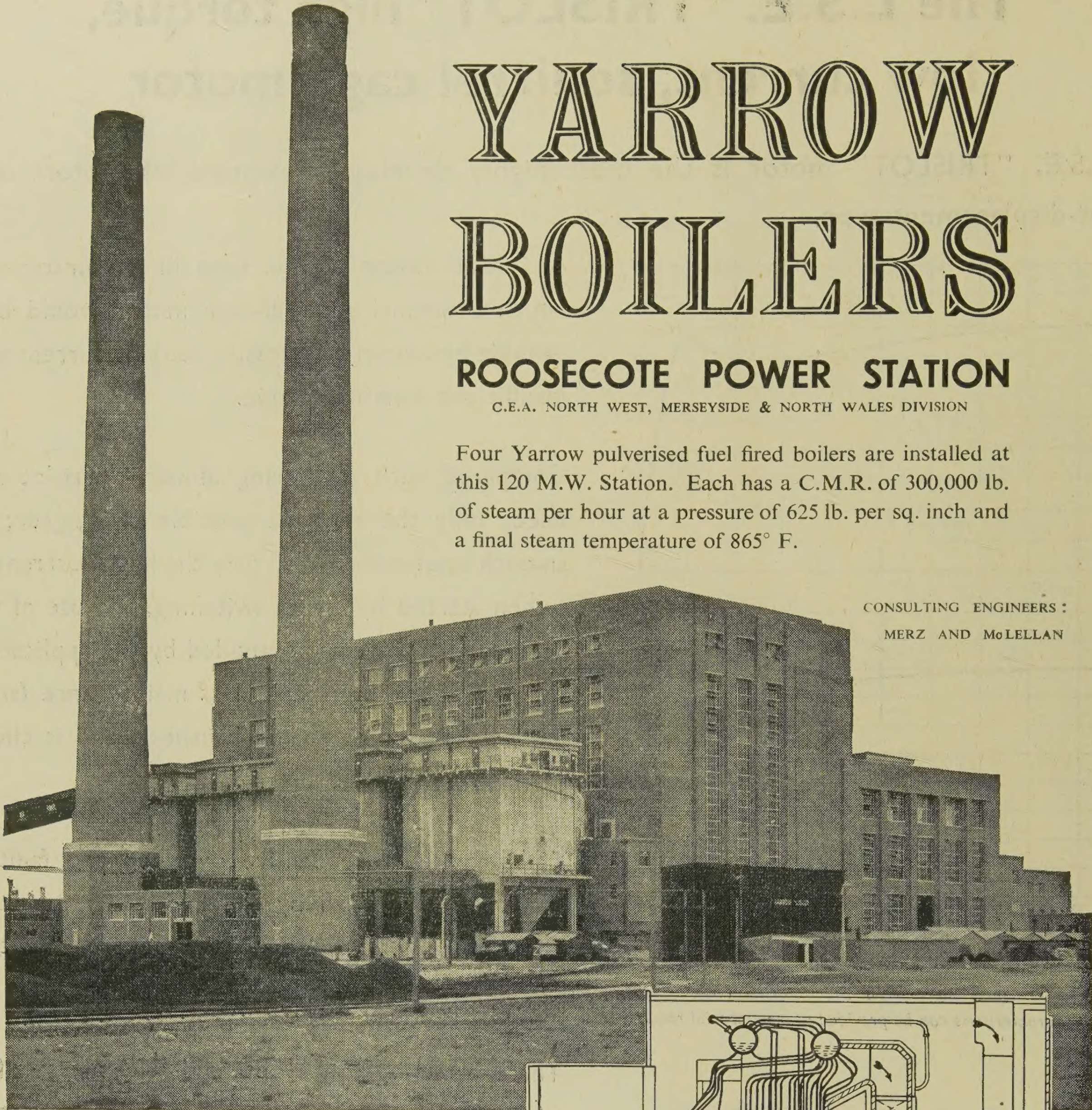

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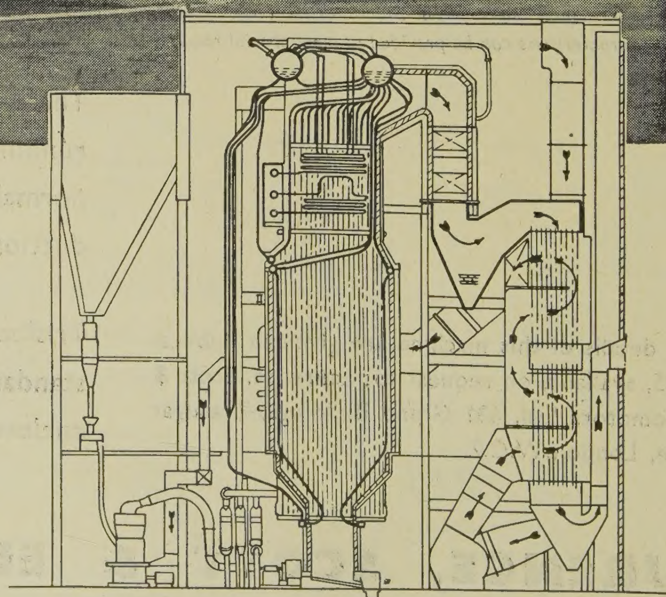

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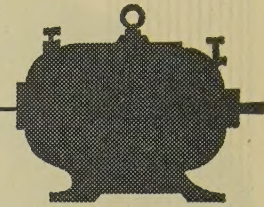

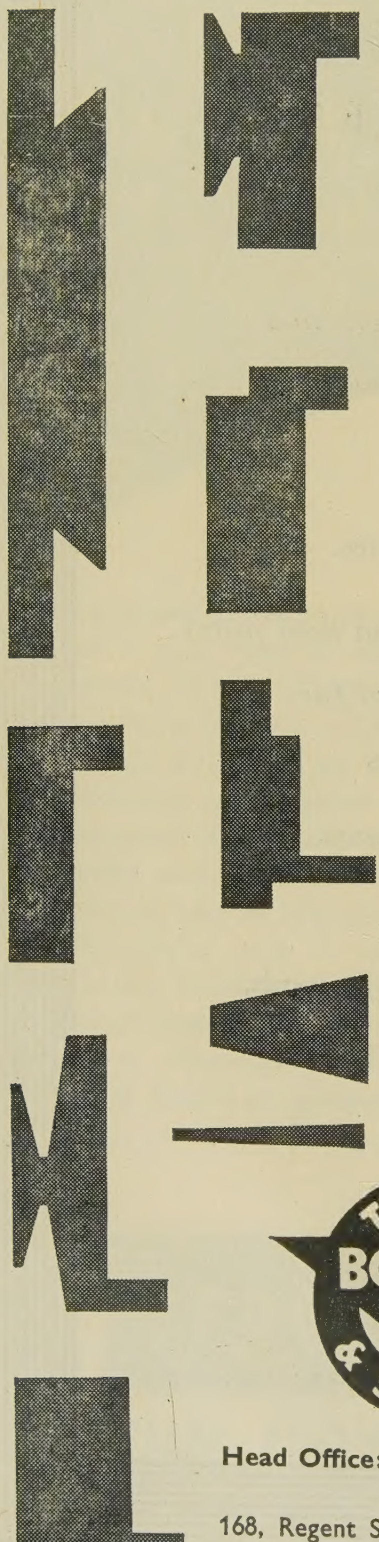

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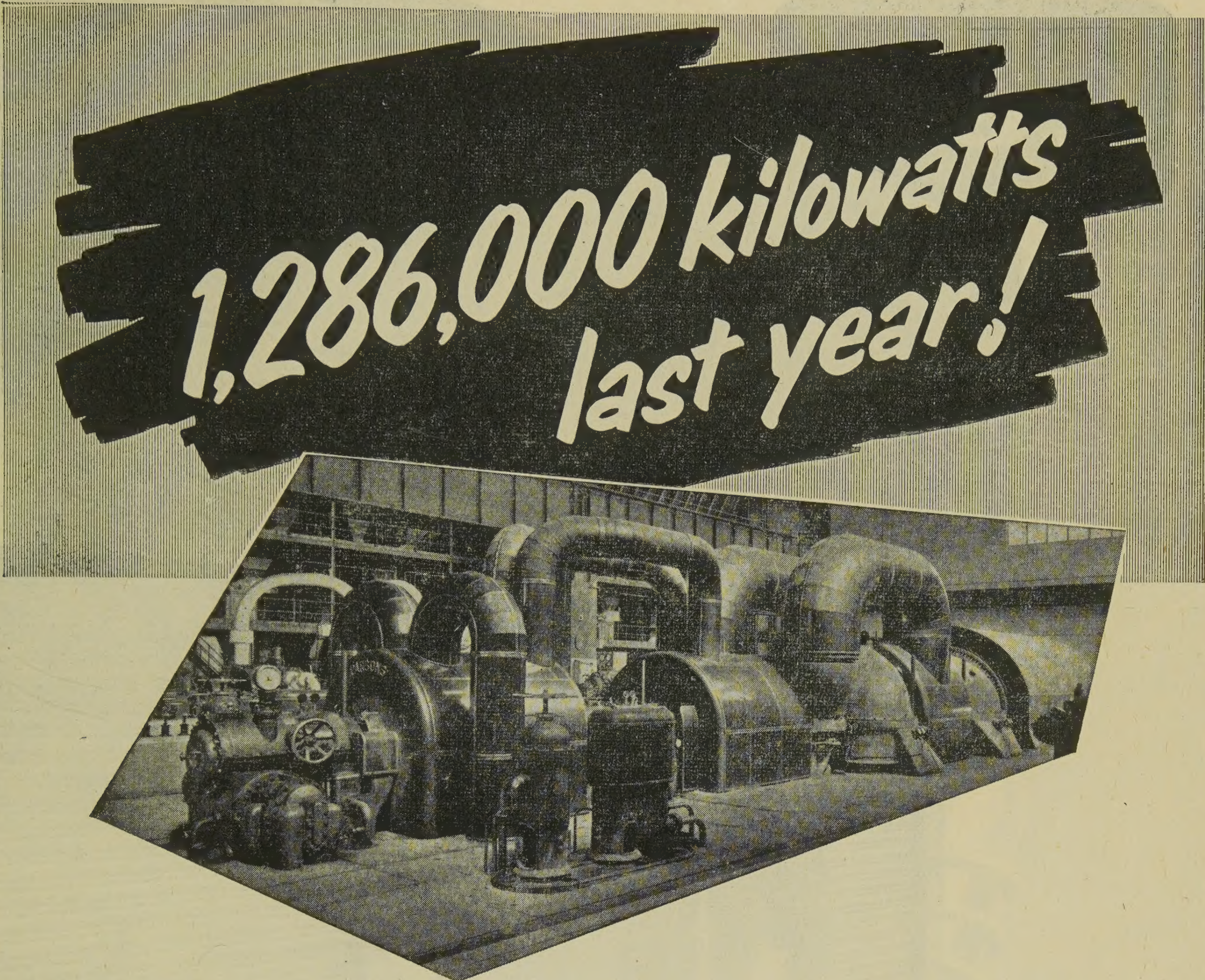
1,286,000 kilowatts
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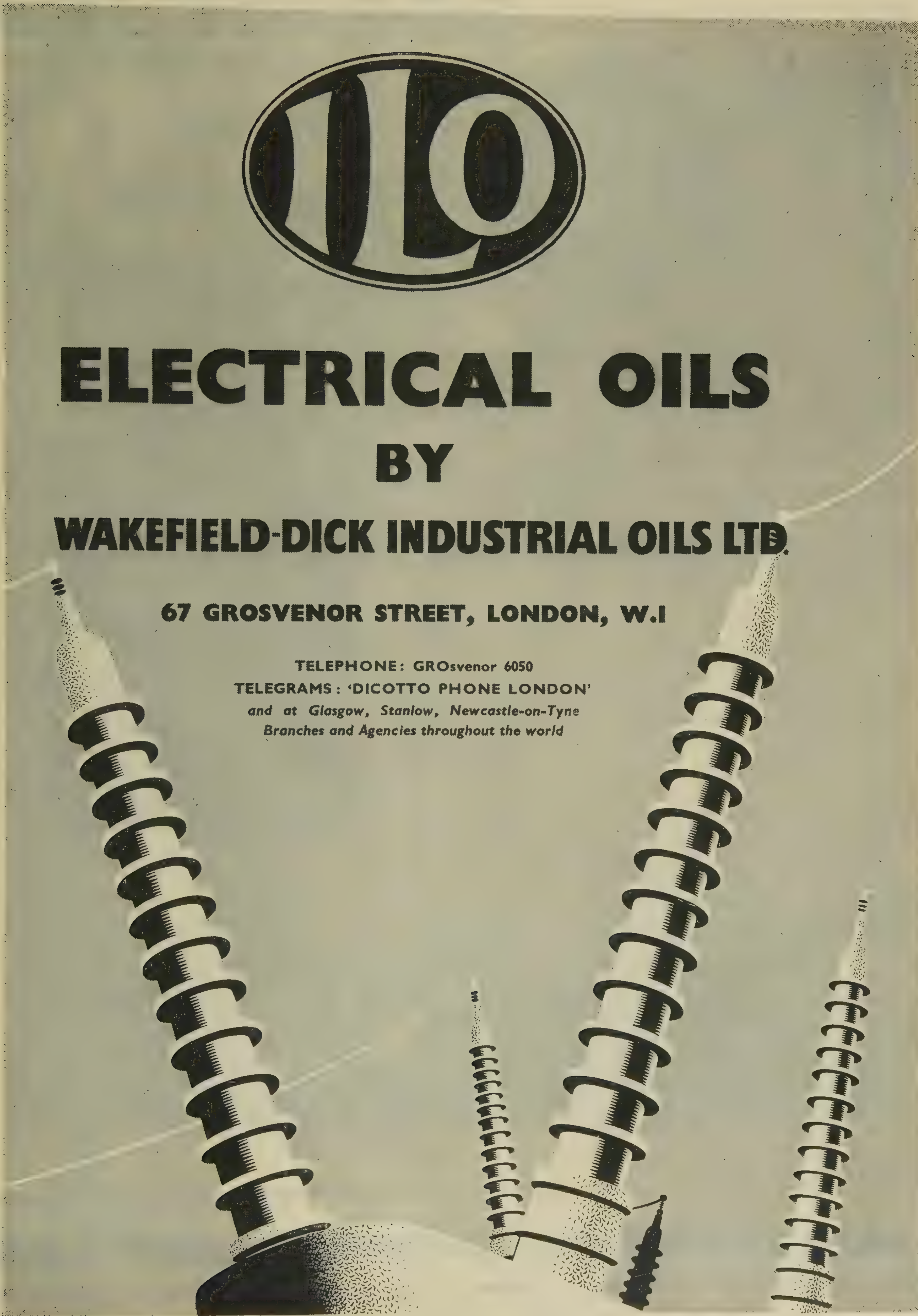
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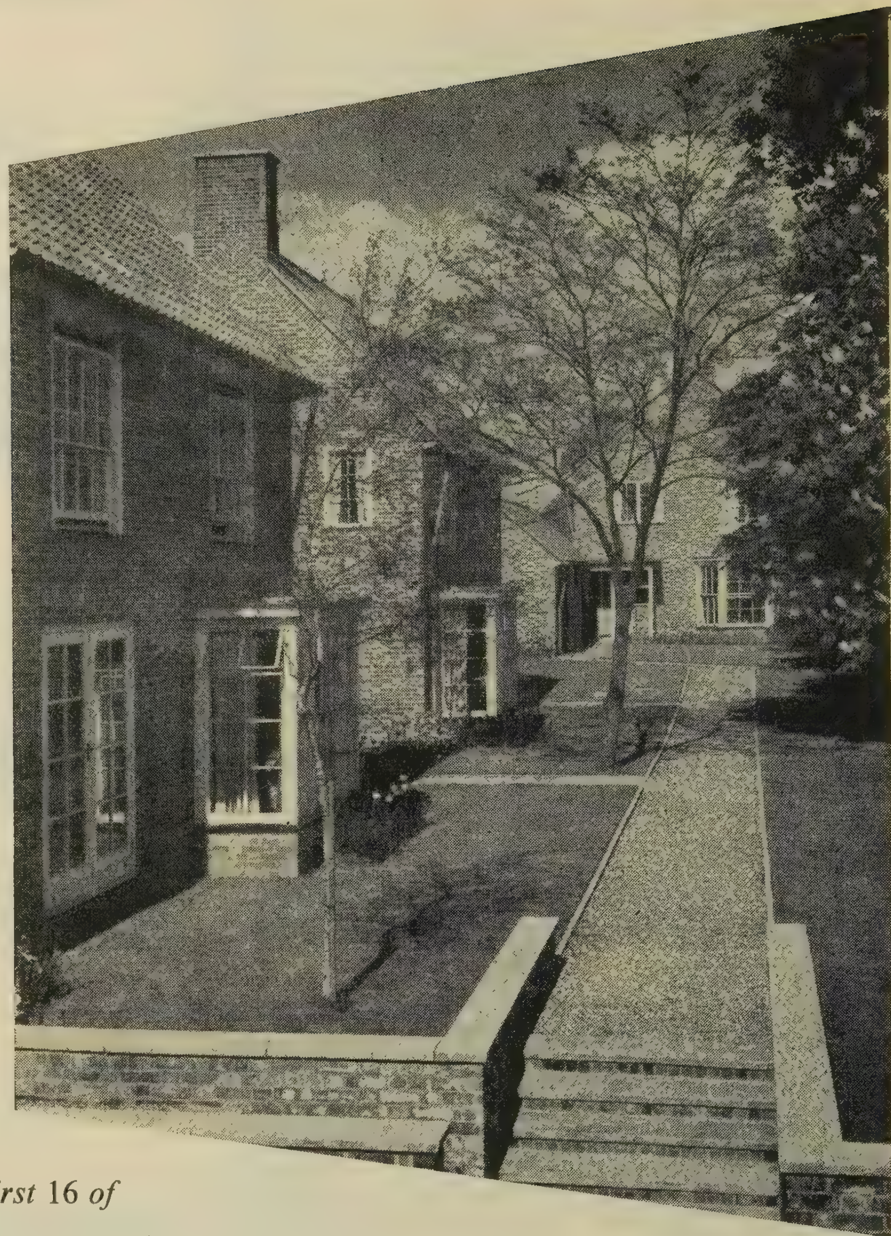


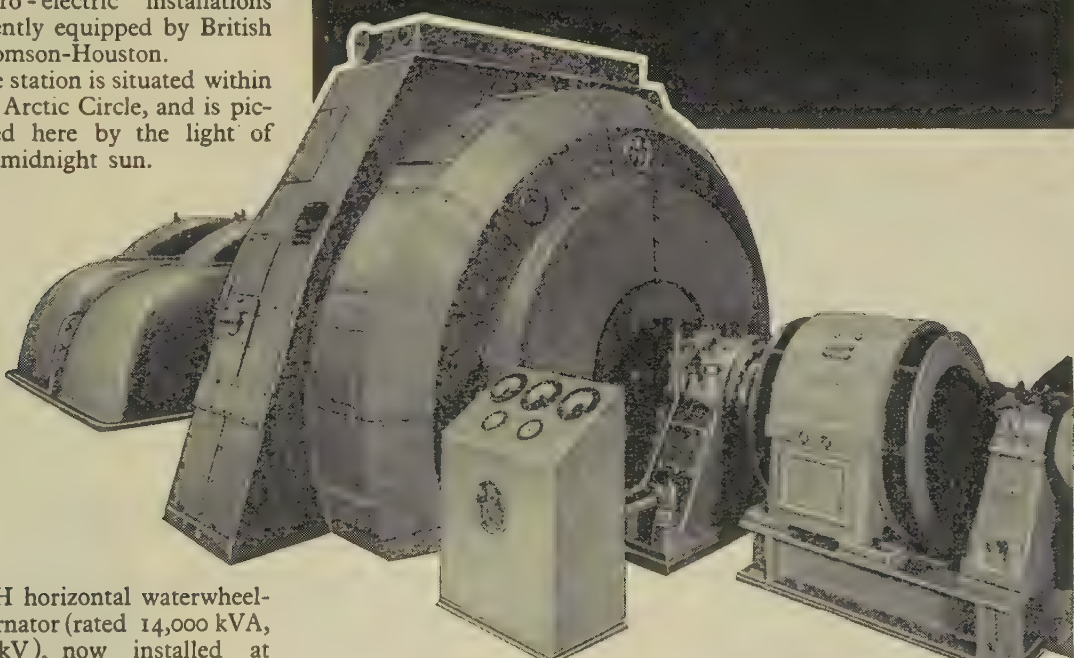
The "Chesters" Residential Estate at New Malden, Surrey, was opened on the 18th May, 1951, and the picture shows some of the first 16 of the 26 homes, which are intended for members of The Institution or their dependants whose needs have come to the notice of the Governors of the Benevolent Fund.

£7,000 is still needed

to reach the £50,000 target

CONTRIBUTIONS HOWEVER SMALL ARE WELCOMED AND MAY BE SENT TO THE HON. SECRETARY OF THE INCORPORATED BENEVOLENT FUND, THE INSTITUTION OF ELECTRICAL ENGINEERS, SAVOY PLACE, LONDON, W.C.2, OR HANDED TO ONE OF THE LOCAL HON. TREASURERS OF THE FUND.

One of several new Norwegian hydro-electric installations recently equipped by British Thomson-Houston.
The station is situated within the Arctic Circle, and is pictured here by the light of the midnight sun.



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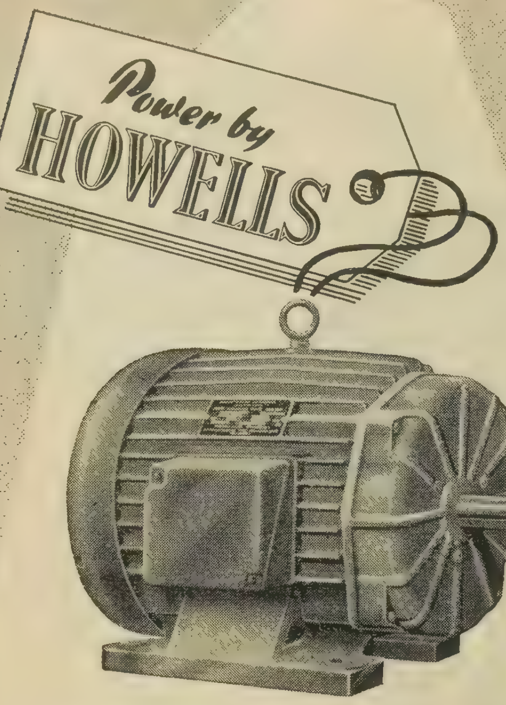

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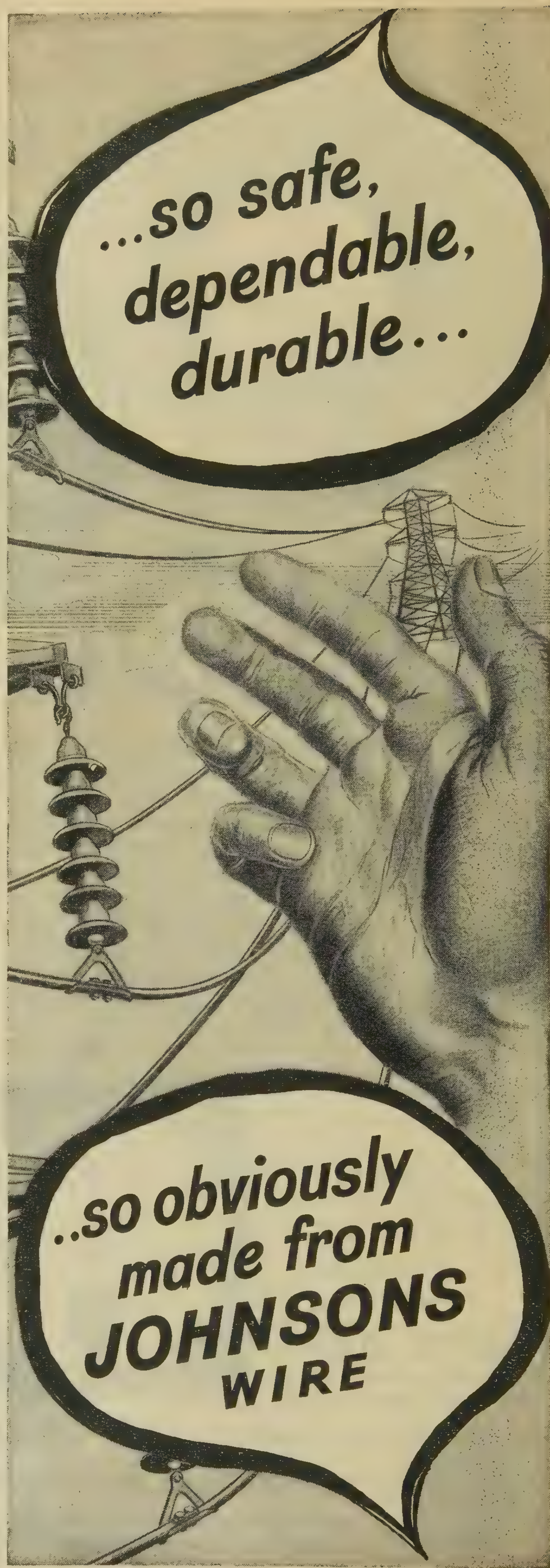
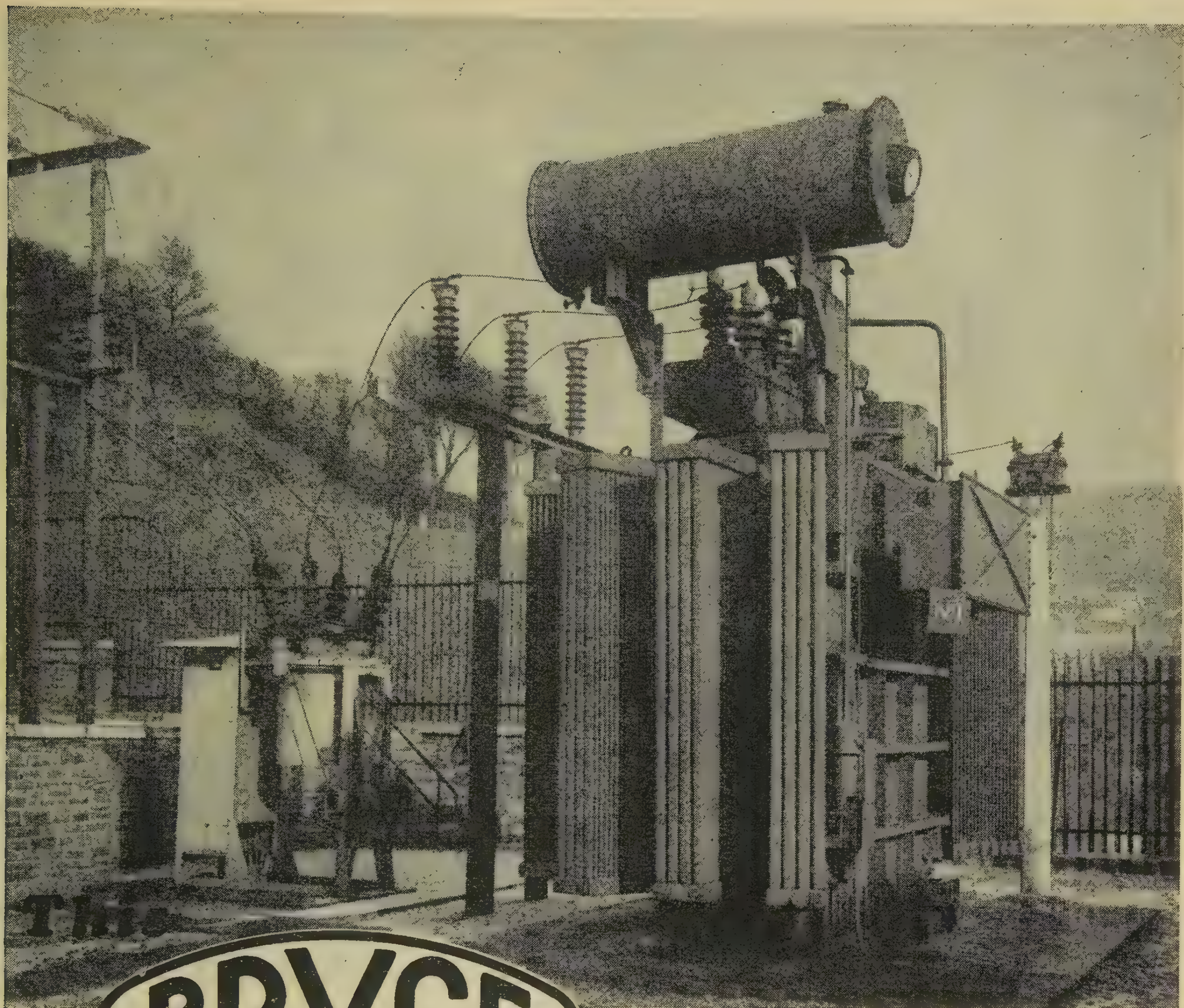
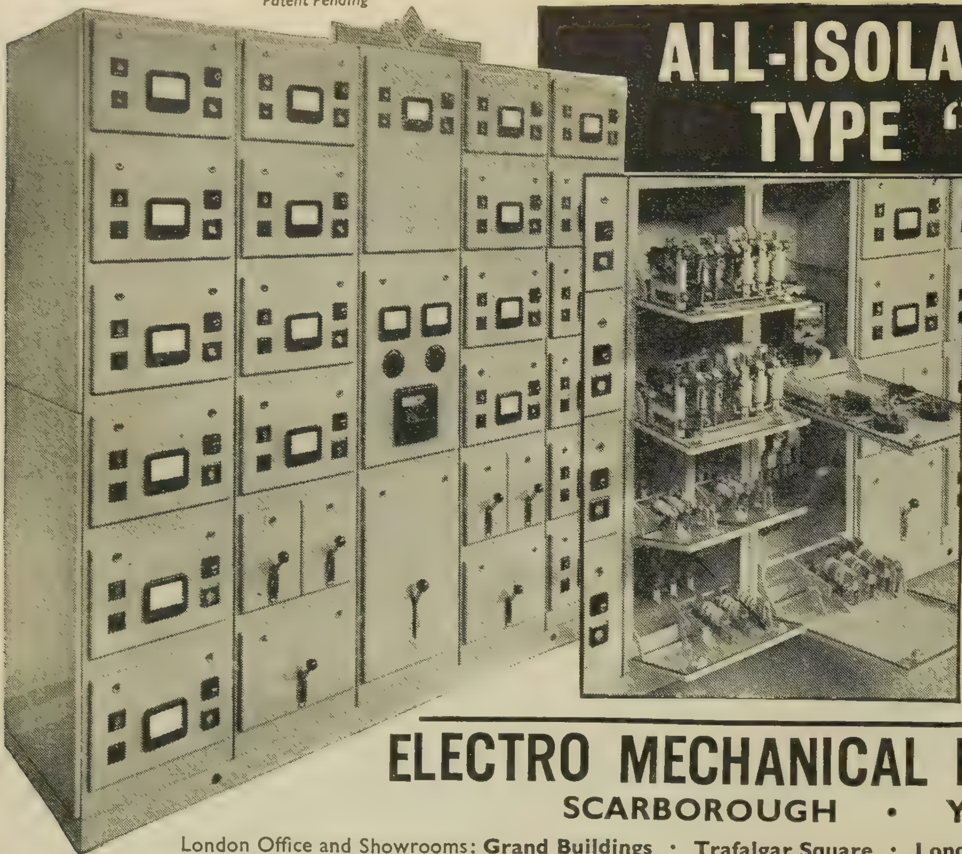


RICHARD JOHNSON & NEPHEW MANCHESTER 11



Patent Pending



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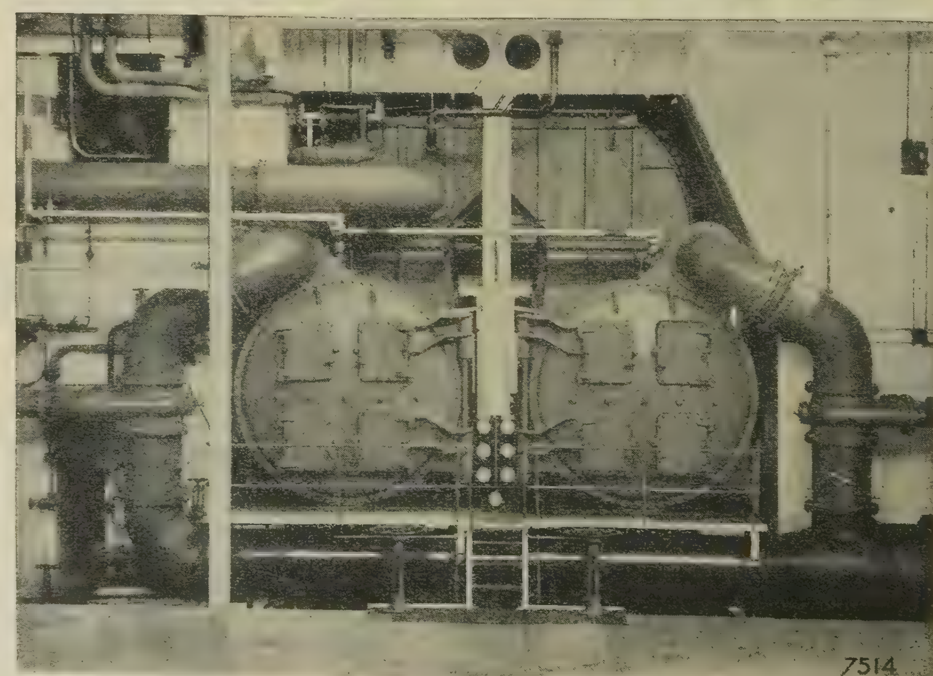

Photograph by courtesy of B.T.H. Co. Ltd.

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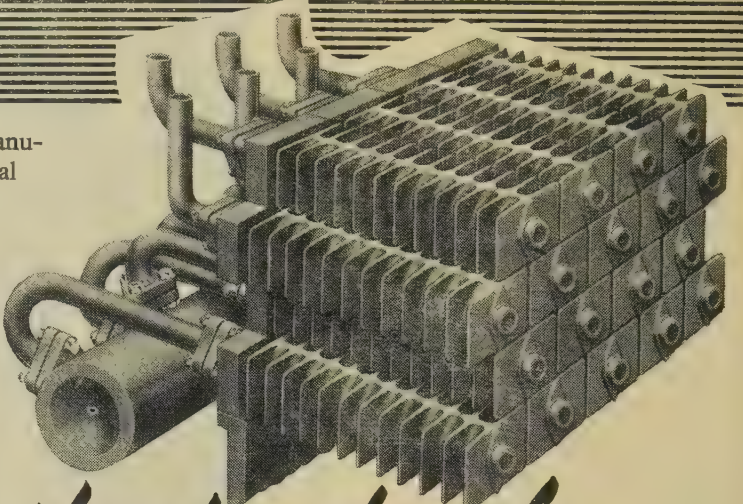
THE PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

TEN-YEAR INDEX

1942—1951

A TEN-YEAR INDEX to the *Journal of The Institution of Electrical Engineers* for the years 1942–48 and the *Proceedings* 1949–51 (vols. 89–98) can be obtained on application to the Secretary.

The published price is £1 5s. 0d. (post free), but any member of The Institution may have a copy at the reduced price of £1 (post free).



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Registrar and Secretary: J. MUIL, M.I.E.E.

Telephone: ABBEY 1737

The Principal Objects of the Bureau are:

(*a*) To receive applications for registration for employment from members who, by reason of their engineering qualifications, belong to The Institutions of Civil, of Mechanical, or of Electrical, Engineers, or persons whose engineering qualifications for election or admission to one of those bodies have been approved by the respective Councils, and to charge and receive such registration fees and engagement fees as may be from time to time determined by the Board.

(*b*) To receive inquiries from employers seeking the services of qualified professional engineers, to advise them, if desired, about the qualifications required for any particular engagement and to submit to them particulars of persons registered with the Bureau whose experience seems to fit them for the appointment.

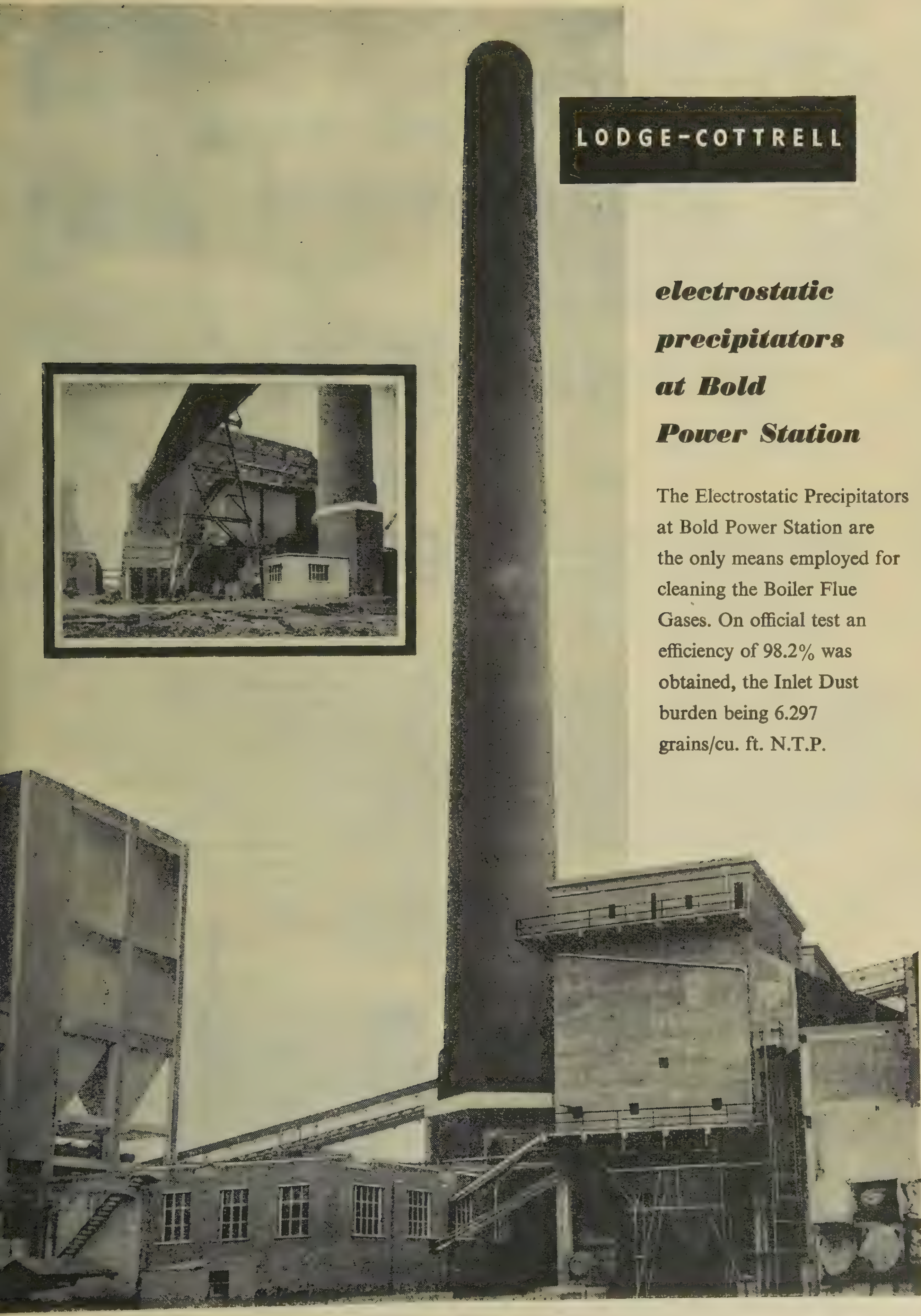
(*c*) To give advice generally about the employment of professional engineers.

The Registrar wishes to draw the attention of all members of The Institution seeking a change of employment to the facilities offered by the Bureau. Appointments, ranging from practical training for Students to executive posts for senior Corporate Members, are notified by employers both for this country and for oversea. Interested engineers should apply to the Registrar for a registration form and should state their class of membership.

EMPLOYERS

Employers of professional engineers are invited to notify vacancies, if possible with the following particulars:

1. Title of post with description of duties involved.
2. Age range (as wide as possible, please, to include where practicable older men).
3. Salary offered and supplementary remuneration, if any.
4. Professional, technical and/or special qualifications, e.g. languages, etc.
5. Location of work.
6. Does the post involve control of staff? If so, to what extent?
7. Any other information which will assist in the selection of candidates.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The Electrostatic Precipitators at Bold Power Station are the only means employed for cleaning the Boiler Flue Gases. On official test an efficiency of 98.2% was obtained, the Inlet Dust burden being 6.297 grains/cu. ft. N.T.P.

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An example of the preferred form of bibliographical references will be found beneath the list of contents.

THE PROCEEDINGS OF
THE INSTITUTION OF ELECTRICAL ENGINEERS

EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

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Paper No. 1953
Oct. 1955

INAUGURAL ADDRESS

By Sir GEORGE H. NELSON, Bt., M.I.Mech.E., President

(*Address delivered before* THE INSTITUTION *6th October*, 1955.)

I am greatly touched by the honour conferred on me by the Council and members of The Institution in electing me President or the ensuing year, and thank you all for this great compliment ou pay me. I shall, with all your help, do everything possible o uphold the traditions and high standards of this great nstitution.

That it should happen in this particular year is especially pleasing to me, coming as it does on the 50th anniversary of my admission to The Institution as a Student Member.

The theme of my Address will be the great prospects and the esponsibilities of electrical engineers in contributing in the uture to the benefit of man everywhere. The subject falls into hree sections—past, present and future.

I will start the picture of the past with our first President, Charles William Siemens, who, it is most interesting to recall, happened to have founded a section of my own Company. I had the pleasure, some two years ago, of presenting to The nstitution facsimiles of his letters giving fascinating pictures of the technical and social life of his time. From this correspondence letter No. 43 shows that, as long ago as 1873, Parliament had moved for the appointment of a Committee "to nquire into the causes of present dearness and scarcity" of coal!

His Address to the first meeting of our Institution—then called The Society of Telegraph Engineers—in February, 1872 (the Society having actually been founded in 1871), was most prophetic. He pointed out that, what to many then seemed to be separate compartments of science and engineering, were eally one, involving a vast range of problems in theoretical physics, applied chemistry, engineering and industrial management, developing into the whole field of electrical engineering s we know it to-day. He said:

> There is hardly a problem in electrical science that is not of practical interest to the telegraph engineer . . . The phenomena of electrification and polarization, of specific induction and conduction, the laws regulating the electrical wave, the influences of . . . temperature on conduction . . . the potential force residing in a coil of wire of a given form, when traversed by a current, involve questions belonging just as much to pure physical science as to the daily practice of the telegraph engineer . . .

nd went on to refer to

> . . . questions of selection of materials for conduction or insulation . . . and apparatus for producing and directing . . . electrical current which . . . call into play considerations . . . of purely mechanical import. . . . I would go further and include statistical information.

He concluded:

> These remarks may suffice to show how great is the field of our activity and how much remains to be accomplished notwithstanding the extraordinary progress of which we are apt to boast.

After this address Mr. C. F. Varley, F.R.S., made most interesting observations, as follows:

> Mr. President . . .
> After your Address, Sir, no one will fail to see . . . this Society . . . will gradually, by natural selection, develop more into an electrical society . . . the moment it is understood that all papers on electricity, or bearing directly upon the development of electrical science are admitted . . . because it will be found ultimately to embrace every operation in nature.

Our Institution, starting in this atmosphere of the widening orbit of electrical science and engineering was to see its original name changed twice in less than eight years, first to "The Society of Telegraph Engineers and Electricians," in 1880, and then to "The Institution of Electrical Engineers," in 1888, when the professional term and title of Electrical Engineer was established.

The work of The Institution and of our profession had progressed so much by 1921 that a Royal Charter was applied for—and was granted, a very fitting honour and recognition of The Institution's central role in establishing high professional standards and propagating and encouraging the science and technology of electricity which has wrought such a revolution in the lives of people everywhere.

Among The Institution's many functions its publication of *Science Abstracts* must rank high in importance, and it is interesting that, at the first meeting in 1872, Prof. Foster, F.R.S., drew attention to the need for a service of this kind.

The three great principles of The Institution's work and policy laid down are:

> (i) To act as a learned society and to provide the means to exchange knowledge in electrical matters.
> (ii) To act as a qualifying body in fixing the standards of knowledge of electrical engineering in its theory and practice.
> (iii) To determine guidance of ethical conduct in our profession.

Our predecessors have striven from the very beginning for the establishment of standards at the highest level, and we and our successors will, I am sure, jealously guard and uphold them.

To refresh your memories on the progress that has been made

in the generation, distribution and use of electrical energy, I would mention that in 1905 many generating plants were of the order of only a few hundred kilowatts, powered by reciprocating prime movers, and that the total generating capacity in Great Britain was 1 700 MW, being only $\frac{1}{20}$ kW per head of population. At the same time in the United States the total generating capacity was 6 800 MW—only a little over $\frac{1}{12}$ kW per head of population.

What immense advances over these figures are shown by to-day's statistics, for by June of this year the total generating capacity in Great Britain had reached 25 500 MW, or $\frac{1}{2}$ kW per head of population—a tenfold increase.

The capacities of individual generating sets have risen in 50 years from a few hundred kilowatts to over 100 MW and, quite recently, sets of 200 MW have been ordered.

In the United States the installed capacity, in the same time, has risen to over 121 000 MW or $\frac{3}{4}$ kW per head of population, and this includes sets larger than 200 MW.

These developments have brought about a steady fall in the cost of electric power in comparison with the cost of living over the past 30 years, amounting to more than 45% in this country and 50% in the United States. The advances in the design of electrical equipment have come from great imagination, courage and enormous expenditure on research and development by the heavy electrical manufacturing industry financed almost entirely from its own resources.

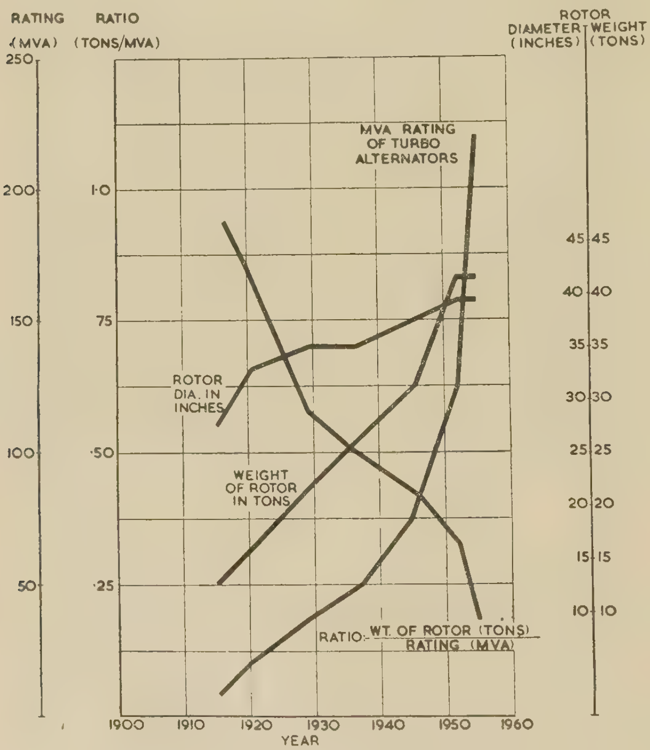

Fig. 1.—Development of turbo-alternators.

Fig. 1 indicates some of the technical changes that have taken place in turbo-alternators in the past forty years. It will be seen that although the output of machines has increased more than 20 times, the rotor weight has gone down from nearly 1·0 ton/MVA to 0·2 ton/MVA, i.e. it has been reduced by 80%. Both these changes have been made possible by new techniques—including the introduction of hydrogen cooling—arising from research. Similar changes have taken place with the steam turbine, through the use of higher steam pressures and temperatures.

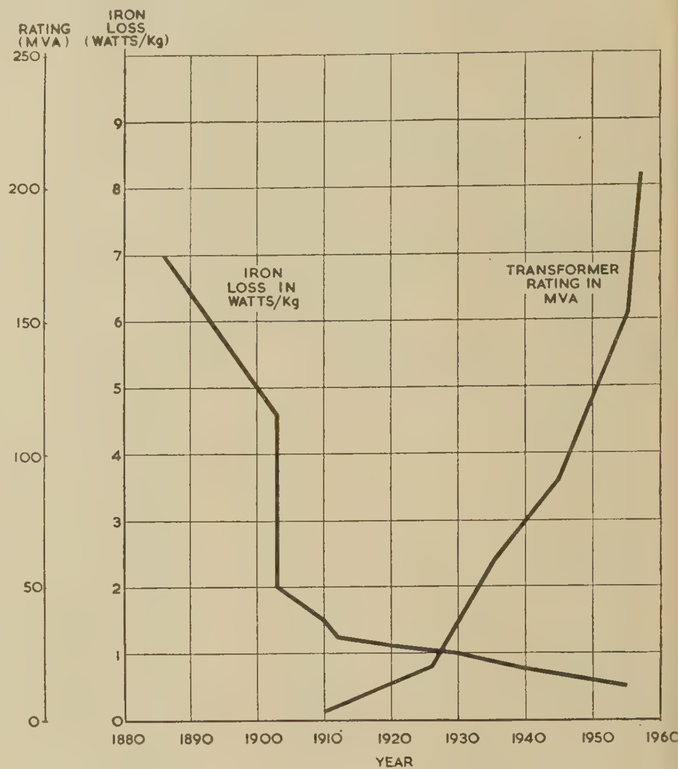

Fig. 2.—Development of transformers.

In distribution, similar spectacular advances have been made. Fig. 2 indicates some of the changes in the design of transformers. The curve shows what a big advance took place about 1905 with the introduction of silicon steel—invented by Hadfield. More improvement is now obtained through grain orientation during the manufacture of the silicon iron. The result has been that the power losses per pound of core iron have been reduced to one-quarter of what they were 50 years ago, and ratings have gone up from 5 MVA to more than 200 MVA, with a rise in transmission voltages from about 6 kV to 400 kV.

As a result of continuous and intensive research and development, corresponding progress has been made with switchgear for dealing with equally spectacular increases in transmission voltages from 6 kV up to 400 kV. Similarly interruption ratings have risen from 25 MVA to 10 000 MVA.

In the telecommunication field progress has been staggering. Fifty years ago few homes had a telephone, Marconi's monumental achievement in transatlantic radiocommunication was only four years old and there was no system of radiocommunication as we know it to-day. The first patent for wireless was only taken out in 1896, and a British Company, formed the following year, was the first to bring wireless telegraphy to the world.

The first public broadcast of news and entertainment did not come until 1920, and the first television service until 1936. Colour television could come at any time now, when the economic position allows it, since the technical problems are mainly solved.

Progress in the application of electrical and electronic control to many important industries is increasing production in a spectacular manner, and also improving quality. An outstanding example is the rolling of sheet steel which, up to 30 years ago, was produced from steam-driven mills in small sheets at a rate of about 2·5 m.p.h. To-day, sheet steel of much more accurate dimensions is produced in coil lengths of 15 miles, leaving the rolls at a rate of nearly 60 m.p.h. The control of liquid and gas

flow and the control of temperatures in the delicate processes of oil refining is another field of important application. What further advance in productivity in other industries will result from a combination of electric power and electronic methods of process and machine control one can only guess, but the fields for such application are unlimited.

Next comes the gain in users' time and in efficiency, by the use of the electronic computing machine, in the solution of research and design problems. These machines are already saving man-weeks and man-months of engineers' and mathematicians' time, solving problems in research and design in electrical, aerodynamic and many other branches of science and engineering. In fact, the availability of these machines has enabled problems to be solved which, up to the present, had not been found possible, owing to the effort needed for their solution.

With these brief comments on the achievements of the past and present, I will now turn to the prospects of the future together with the problems that will be associated with that progress.

From my extensive travels oversea, and from discussions with those carrying the highest responsibility in the many countries visited, particularly since the end of the 1939–45 War, I have found an almost unanimous determination—not just a hope—I repeat, a determination, of all nations—whatever their race, creed or state of development—to improve their standard of living, and they all realize that the key to this lies in the greater application of electric power to the source of their national economy, including agriculture, communications and industry. In other words, economically, they all have an expansionist policy.

To the electrical engineering profession and industry this brings increased responsibility now, with a steadily increasing demand for engineers and for electrical equipment by the pressure of more and more people everywhere, as the population of the world increases.

Let us briefly review the prospects of the growth of the world population. Estimates given by Palmer Putnam in his book,* and also statistics issued by the United Nations, show that the population of the world has risen from 1 100 million in 1850 to 2 400 million in 1950. Over half of that population are living in areas where there is an immediate and continuing pressure for improvement in economic standards.

It is estimated that by the year 2050 the world's population will have increased to $2\frac{1}{2}$ times the 1950 figure, reaching the gigantic total of 6000 million.

These estimates of world population cannot, of course, be taken too factually, because of the difficulty of obtaining reliable censuses in the under-developed countries; they can be nothing more than rough estimates, but they suffice to indicate that both living standards and world population, steadily and substantially rising, will increase the demand for more and more electric power.

At the recent Geneva Atomic Energy Conference, Prof. Robinson and Dr. Daniel said that by the year 2000 the world consumption of energy would be not less than the equivalent energy of 7 500 million tons of coal a year, representing a threefold increase in total energy consumption in the next 50 years.

These prospects compel us to recognize the needs and compel us to solve the problems which will arise from the steady exhaustion of conventional fuels and basic materials which will be used in meeting the needs of the increased population and the higher standards of living which they will expect.

Fortunately, under the pressure of the need to defend our way of life, we carried on great research and development in the field of nuclear physics through which—by Providence—scientists, technologists and engineers are finding a solution to the exhaustion of conventional fuel in the development of the basis of the means of generation of electric power from nuclear energy.

* "Energy in the Future."

I had intended to make considerable reference to the bright future in this field, but so much has been said and written, since I framed this Address, that I feel you are all reasonably up to date with the position, and I will simply say, therefore, that the progress made in this field of nuclear energy forms one of those miracles which occur from time to time, at the appropriate moment, to meet the needs of mankind.

The solution of the fuel problem in the generation of electricity is therefore undoubtedly in sight, but we must not for one moment think that this is the only problem with which we are faced in meeting the needs of improving the standards of living of the world and of a growing population. However, just as research and development in nuclear physics provide an alternative source of heat for generating steam, so equal and intensive study, research, and development in fundamental physics will provide alternative sources of supply of other basic materials, and this must be followed up immediately.

The measure of urgency arises from the fact that 90% of the present population of the world has a standard of living below that in the United States and Great Britain, and it has been estimated that if the standard of this 90% were raised overnight to that of Great Britain, the resources of basic materials like iron and copper, etc., would be exhausted in 25 years. Progress, thank goodness, cannot take place at this rate, but it does indicate that the rate of exhaustion may easily become an acute problem in 100 years. One hundred years is a very short period, in normal times, in which to solve problems of such immense and fundamental character as producing appropriate artificial substitutes, and/or producing synthetically basic metals in quantities as the result of recent research into transmutation or synthesis of a heavy element from a lighter one.

Prominent in the field of production of artificial substitutes are the cellulose products. The possibilities in this direction can be measured by realizing that the energy which reaches the earth from the sun every day is estimated to be at least 50 000 times the total energy produced from all man-made engines in the world to-day—i.e. electrical generating plant, motor cars, ships, etc.—and it is this solar energy which provides the base of cellulose pulp.

In visualizing the possibilities of artificial fibres, I would mention that Terylene fibres have physical properties comparable with steel, which indicates that in time means may be found of economically producing materials in suitable forms as a substitute for steel for structural purposes, making it possible to conserve the use of iron ore to make steel for its magnetic or other special properties.

Similarly, a synthetic material has been produced from which is now manufactured, among other things, pipes, for conveying hot, cold or corrosive fluids. This is replacing copper or lead at a fraction of the price and with less liability to corrosion, and so helps to conserve two metals whose supply is rapidly diminishing.

What immense possibilities towards meeting the needs of the future this picture presents, and how important it is that it should also have immediate intensive study and attention.

Although it has no bearing on the value of solar energy which reaches the earth to-day, I cannot conclude my reference to energy from the sun without reminding you that normal fuels, such as coal and oil, used to-day for power generation, received their stored energy from the sun, and, of course, the falls of water generating hydro-electric power spring from water originally evaporated by the sun's energy making use of the earth's contours.

I feel that the Council and the members of The Institution

are to be congratulated on their vision in agreeing that The Institution should play its part in forming and becoming a founder of the British Nuclear Energy Conference in association with the Institutions of Civil, Mechanical and Chemical Engineers and the Institute of Physics. To make most rapid progress from research and development in the field of nuclear physics it is necessary to embrace the sciences, the technology and the engineering of all these Institutions, and therefore the establishment of this conference is of great national importance.

It cannot be denied that outstanding benefits have come from development initiated or extended to create the means of destruction. It is now possible that the latest discoveries of our scientists and technicians of the hydrogen bomb may make the risks of war so terrible that man will not face the consequences of the possible annihilation of our species, and therefore some political solution will be substituted for war—anyhow war between industrial nations.

It is indeed providential that science has put such an instrument at the disposal of our statesmen, and I sincerely hope they will be successful in convincing possible aggressors that war cannot be contemplated.

Even if this is successful, I feel that armies and navies will still not be completely abandoned, for some will be necessary for policing the world to deal with minor situations, but they will be in much smaller measure, and consequently it will be possible to release a considerable number of scientists, technologists and engineers from the study of the means of the destruction of man in order to play their part in the improvement of world conditions. Pride can be taken in the results which have so far sprung from the remarkable co-operation between scientists, industrialists and the Government in war time. It is heartening to find that our Government is continuing to pursue a similar policy in peace time in the field of nuclear physics, the research and development of which are enormously costly and which could not possibly be borne by individual firms.

I must issue a warning that the release of scientists and technologists from activity on war equipment will not be sufficient to solve all the problems to which I have referred in my Address, and The Institution, therefore, must continue to play its part in pressing for still greater facilities, and to continue to advise on the methods of education and training of electro-technical scientists and technologists, in order to overcome the shortage of technical manpower, not only in this country but also in the Commonwealth.

The Institution is to be congratulated on the steps it has taken with industry in producing its film entitled "The Inquiring Mind," with the object of attracting the interest of parents and boys in science and technology, thus stimulating recruitment in these fields. I sincerely hope it will be successful in convincing both parents and boys that the study of science and engineering can be just as powerful in forming well-rounded human minds and will develop at least as good character as the traditional subjects which we know as the Humanities, and are professions of high standing providing stable employment and great scope. It is particularly necessary to attract a great proportion of the young people who still choose to pursue the Arts at various levels, in spite of the need for technologists for the improvement of the world. Another possible source of supply would be by influencing young men who are potentially good, but who take no further steps to carry their education to the graduate standard.

Further interest, I feel, could be stimulated by increasing substantially, with necessary supporting facilities, the numbers of well-qualified teachers in mathematics and science subjects in secondary schools; also by arranging that effective steps are organized continuously and clearly, explaining to boys who have reached the General Certificate of Education level the opportunities of a career in scientific rather than non-scientific subjects, so influencing the transfer of promising boys from one side to the other.

Parents' interest could be stimulated by readjustment upwards of the facilities for awarding scholarships, particularly to help parents who have several children to educate. It is important that technical colleges not affected by the Minister's recent announcement of the upgrading of certain technical colleges to university standard, should not be lowered in standards or facilities. In fact there should be an extension rather than any curtailment. Also, if a student following a part-time course shows great promise during his development, he should be transferred to a sandwich course or full university course.

But I would emphasize that there is great scope for careers masters at schools who have that rare gift of being able to assess a boy's potential development, and they must be given the facility to push forward boys of special ability and to encourage their enthusiasm for their work.

Fig. 3 indicates the seriousness of the position by contrasting the total university population—all subjects—over the years

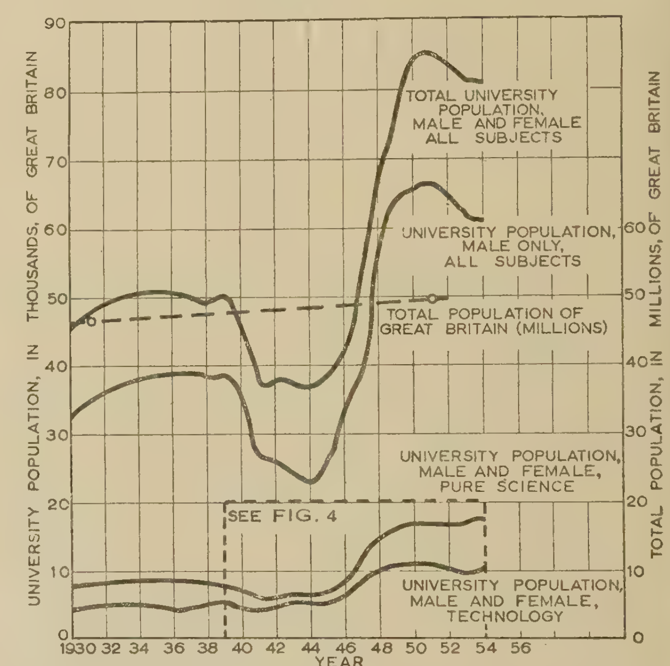

Fig. 3.—Analysis of population of universities in Great Britain.

from 1930 to 1954 with the numbers of students taking full-time courses either in science or in technology (of which the greater part is engineering). Fig. 4 gives, on a larger scale, information of the trend in recent years for pure science and for technology. The curves show the low proportion which science and technology students bear to the total number of university students in Great Britain; also that, even at this low level, technology has not kept pace with pure science, and that in both these cases the post-war increase has levelled off.

As an industrialist who makes a substantial demand on the supply of technical personnel, and who, to help the position generally, has set up very great resources for practical and advanced specialized training of appropriate young men, I have supported wholeheartedly the policy worked out by the Council's expert committees, for I believe they have interpreted correctly the present needs of the whole industry and foreseen properly the future technical demands that will be made on the men concerned some years after their graduation.

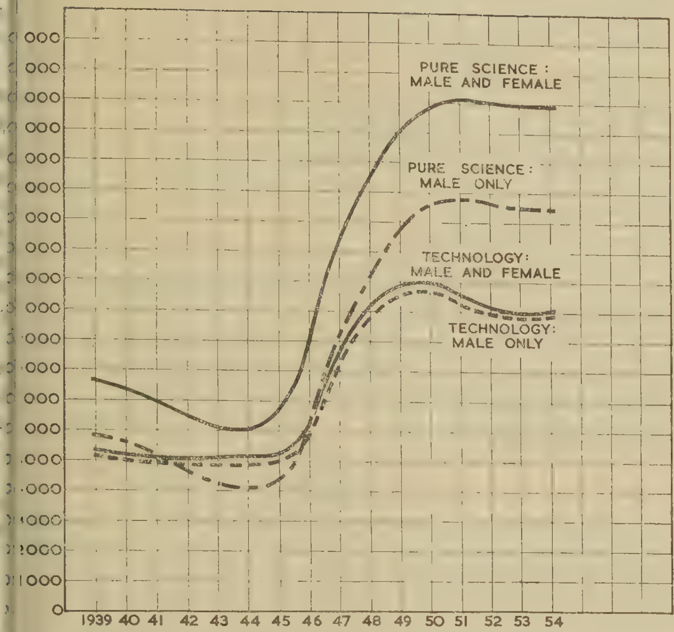

Fig. 4.—Analysis of university population in pure science and technology.

I would say that I support very strongly the warning issued by e Barlow and Percy Committees—that on no account must the mand for quantity be allowed to lower the standards of quality. would say that remarks have been made to me, both at home d abroad, which implied that some people think that The stitution is raising its educational requirements above what is cessary, implying also that it was limiting recruitment to the ofession. I vehemently denied this and pointed out that thing was further from the truth for, on the contrary, The stitution, while supporting the policy of increased quantity th quality, was pursuing an energetic campaign to attract a ger share of the output of boys from secondary schools to ke engineering courses and so increase the input to the chnological field and, if of appropriate qualifications, to embership of The Institution.

A very important phase of the supply of technical personnel the special, great and urgent need for technically qualified en who have the natural gifts for management and highest ministration. The ideal men for such appointments unubtedly are those who are qualified in science and technology d who, in addition, have the inborn qualities of character, wers for leadership and that rarest of all senses—common sense the combination of which earns the respect and confidence of hers.

Such qualities are born in men and are not made by education. e greatest problem is to catch the person as soon as these aracteristics appear, and to develop his natural gifts in assoation with scientific and technical education. I am sorry to y I cannot write a specification for somebody to use for the lection of such men. I can only suggest that the supply could increased by appointing as school careers masters men who ve the gift of spotting them, and who can ensure that they ceive appropriate training.

I suggest that the careers masters at schools and colleges with the gift for recognizing those with management qualities can do much to help in this work. The adequate supply of future managers is fundamental, because the best results from design, manufacture and operation can come only with efficient management intimately familiar with the widest aspects of the business concerned.

Great Britain has very few natural resources and without doubt its scientific, technological and skilled people are its greatest economic asset. This being so, they must be employed in the most efficient manner and their use on duplication or further multiplication of effort on the same problems should be avoided, in the interests of the nation and Commonwealth.

Unfortunately, we have not yet reached that degree of rationalization in industry necessary to achieve this important position, which is essential in order to obtain the lowest cost of production, enabling Great Britain to compete successfully in the greatest possible measure in the markets of the world. This it must do to meet the needs of its growing population and of an expansionist world economic policy, so as to achieve for Great Britain the maximum effort in order to pay for the increase in imported materials so necessary if we are to increase our output. Success in these two roles necessitates the importation into Britain of goods and materials which do not exist in this country, and the exportation of further goods to pay for the increase of material so necessary for extending our output to meet increasing world demand.

The deep interest of Members in this matter was apparent to me during my visits as Vice-President to the Centres and Sub-Centres where, in almost every area, questions were raised about the need for more papers on the management and practice of research, manufacture and operation of electrical machinery and on equipment in all fields. I sincerely hope that the Council and the Papers Committee will take note of this, and that Members who can present such papers will respond to this very important request and so add to the continuous improvement in production and operation of electrical equipment.

I feel that, great as the Address of the first President, in 1872, was, at that time there were no fears about the imminent exhaustion of supplies of basic materials. Neither did this question seriously arise as recently as 50 years ago, but to-day the effect of increasing demand and growing population on the world resources of materials has inspired the theme of my Address.

This is not a vague question for the future, but it is with us to-day. If a lowering of the standard of living through the exhaustion of natural resources is to be avoided, immediate action to produce synthetic substitutes of all kinds must be taken now. Electrical engineers will have to play a prominent part in these developments, which, in turn, will bring increased responsibilities to The Institution for ensuring that adequate numbers of qualified electro-technical scientists, technologists and industrial administrators are available for this vital work, which responsibilities will undoubtedly be met.

In conclusion, I would thank you once again for the honour which you have bestowed upon me in electing me as your President, and for your patience with, and attention to, my Address. I would like to pay special tribute to the achievements of the Presidents, Members of the Council, and Secretaries, past and present, who have established The Institution at such a high and valuable level among our national institutions.

Abstract No. 1975,
Feb. 19

SUPPLY SECTION: CHAIRMAN'S ADDRESS

By L. DRUCQUER, Member.

(Abstract *of Address delivered 26th October*, 1955.)

Prior to the industrial revolution, power, under the control of man, came from water, wind, animals and human beings. Whilst the ultimate potential of these sources is so great as to be almost incalculable, the source most readily available and easiest to hand was human energy, augmented by the harnessing of animal power. It can roughly be estimated that the potential human energy available is considerably greater than the present installed electrical generating capacity of the world. It is, however, obvious that such power source is spread too thinly over the earth's surface and that reasonable concentration is too difficult to accomplish.

It was James Watt in 1764 who first produced a practical steam engine which made it possible, and economic, to concentrate power at given locations. Thus was born the industrial revolution which, in its triumphal progress, ate deeply into the long-established and zealously guarded crafts which had until then formed the basis of our civilization. Coal became the dominant factor in the life of the country, changing materially all previously accepted concepts and launching mankind on the slippery slope of attrition in which we daily consume a large proportion of our natural and irreplaceable assets.

As a result of Michael Faraday's researches in electromagnetic induction, the way was prepared for the generation of electrical energy and its conversion into mechanical power, and after many attempts, machines capable of heavy current output were demonstrated in 1867. With the advent of the electrical generator the horizon again expanded, since the world was now in possession of a form of energy which could be converted readily into both mechanical power and light, and which, moreover, could be distributed over a considerable area without difficulty or undue loss of efficiency.

In the middle of the 19th century the world became conscious of the potential power of oil as a challenge to coal, and over the years oil has grown to the extent of providing some 25% of world energy, compared with 60% derived from coal, 10% from water power and 5% from natural gas. The process of attrition continues, however, and, in the case of oil, it continues at such a rate that if future consumption confirms present-day estimates, it may well have become exhausted early next century.

Thus, some 90 years ago, the science of electrical engineering was founded, and it has developed at such a remarkable pace that it has revolutionized the world, and now so permeates our lives as to have become the cement which holds together our modern way of life. The electrical industry, which had become well established by 1905, can, in the main, be divided into two major parts—manufacture and supply—both essential and completely complementary one with the other.

The manufacturing industry is probably unique in that not only is it the sole manufacturer of every form of apparatus which consumes electricity, but it also manufactures the plant necessary to produce this electricity. Its rate of growth has kept pace with, and in fact has been primarily responsible for, the advance of electrical science and the growth of electrical energy consumed. It is estimated that in 1954 the 685 000 persons employed in the industry produced electrical apparatus to th value of £750 million.

Whilst it is difficult to find a representative yardstick agains which to measure the growth in efficiency of the industry, no suc difficulty exists in respect of the apparatus it produces, as th following examples illustrate.

Generation

The fact that the average size of turbo-generator installed b the C.E.A. in 1954 was about 50 MW, and will rise by 1962 t 140 MW, underlines the increase in rate of growth which is no taking place. This is the more marked when it is appreciate that the maximum size of set so far included is 200 MW, wherea already sets of 300–400 MW are being contemplated.

Of recent years both pressures and temperatures have increase rapidly. They have risen from the immediate post-War stea conditions of 600 lb/in^2 850° F, quickly through an intermedia step of 900 lb/in^2 900° F to 1 500 lb/in^2 1 050° F, which represen the steam conditions of some recently commissioned plan Consideration is now being given to future pressures o 4 500 lb/in^2 or more and temperatures of 1 100° F or greater Such striking advance in the size and operating conditions of th turbo-alternator units has had considerable reaction on the vita matter of thermal efficiencies.

The average thermal efficiency of all power stations of th Central Electricity Authority (including those now operated b the South of Scotland Board) has shown a marked improvemen of recent years and should rise more steeply as the larger unit come into commission. The figure of 28·75% represents th average of the best 20 stations in 1955.

Whilst the electrical rating increases, the physical size doe not grow at the same rate, and by the better and more skilful us of both old and new materials and adoption of new technique the overall volume per kilowatt has been materially reduce The volume per kilowatt for complete power stations has bee more than halved over the last eight years, although such savin does not result only from improved apparatus design an increased size of unit, but also from new approaches to layout and the use of semi-outdoor auxiliaries. The possibility o greater adoption of semi-outdoor boiler arrangements, such a that at Ince power station and others still to be commissioned will further contribute to the downward trend.

Increase in electrical rating cannot be achieved by mere proportionate increase in physical size, because of such relate problems as safe peripheral speeds of blade tips and electrica rotors, and difficulties of transport. Advanced mechanica design, coupled with the use of direct hydrogen cooling of bot stator and rotor at relatively high pressures, has greatly aide the reduction in size per kilovolt-ampere. The increase in stea pressure and temperatures has created problems of which blad and cylinder casing design, shaft distortion and expansion ar representative. Such problems have been solved only as a resul of intensive metallurgical research and by such arrangements a double-walled cylinders, etc. Whilst the necessity for it is fully realized, the onerous conditions imposed by double-shift working

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the largest units now projected add materially to the difficulties in the design and ultimate operation of such sets.

Transformation

The growth in transformer capacity again underlines the fact that over the last few years the rate of increase in size continues to grow, the maximum rating having more than doubled in the last four years.

In this country the largest transformers are transported by road, and their design is thereby limited both in height and weight. Height is, of course, fixed by existing over-bridges, but weight is limited only by the present ruling of the Ministry of Transport, which fixes the maximum permissible gross weight of the loaded vehicle at 200 tons. The actual transformer weight is therefore restricted to about 150–160 tons, which, based on present designs, would represent a maximum 3-phase transformer size of the order of 200 MVA.

The growth of voltage has been more uniform over the years but, here again, the rate of increase over the last few years has become steeper. Progress in design of large power transformers has developed along fairly definite lines, apart from the means of dissipating the heat generated by the transformer losses.

At the close of the 19th century, transformer cores were made of ordinary hot-rolled iron, which, however, was soon discovered to suffer from ageing, thus causing rapid rise in iron losses, consequent overheating and ultimate premature breakdown. Early in the 20th century, non-ageing silicon alloy was first produced, and by continuously improved methods of rolling, heat treatment and quality control, steel makers evolved the hot-rolled silicon steels of the 1930's which resulted in the core loss being halved. The development of a new rolling technique resulted in silicon steel being produced in the form of cold-reduced oriented strip, which, owing to the "lining up" of the individual magnetic crystals, is more easily magnetized and can be worked at a higher flux density. Thus, for a given loss, the core section can be reduced, permitting shorter copper length, smaller copper loss, reduced overall dimensions and lower oil volume.

Rectification

There still remain certain specialized processes and uses where direct current has the advantage, the chief applications being traction and electrochemical; the latter usually demands extremely high currents.

Little change has occurred in maximum rating over the last 25–30 years. A size of about 4 500 kW meets the maximum requirement, and further power demands are obtained by paralleling units. In the last fifty years methods of large power rectification have, apart from the motor convertor, been subject to considerable change, progressing from the rotary convertor to the water-cooled mercury-arc rectifier and thence to the present-day pumpless sealed rectifier.

Following original German research, the mechanical contact rectifier has been developed in this country during the last five years, and a 260-volt unit having a rating of 3 900 kW 15 000 amp has operated satisfactorily over considerable periods in commercial service. The mechanical contact rectifier is a device designed to open and close circuit contacts 50 times a second (on a 50 c/s supply), which, on continuous load such as that represented by electrochemical duty, may amount to 1 600 million operations per year.

As the result of the tremendous advance in light power rectifiers of the semi-conductor type, such as germanium, much research effort has been, and is still being, concentrated on the development of heavy power rectifiers. The results, so far, have been most encouraging, and units of 300 kW have been running on industrial service since late 1953, whilst units of up to 2 300 kW and 13 000 amp are now under construction.

The change in method of rectification from rotary convertor to water-cooled and pumpless mercury-arc rectifiers produced only a relatively small improvement in efficiency except at very high direct voltages, but with the introduction of the mechanical contact, and later, germanium, rectifiers a significant gain in efficiency has resulted, especially at low voltages, where values as high as 98·8% have been reached. This increase has been achieved with a marked reduction in volume, and once again the real progress lies over the last five years, during which the output per cubic foot has more than trebled.

Control

The growth in size and numbers of generators and the interconnection of stations have resulted in ever-increasing levels of fault MVA, demanding switchgear of greater breaking capacity, and in recent years a most marked increase in rate of growth is apparent. Values in this country have more than doubled, to reach 7 500 MVA in the last seven years.

The challenge of growing MVA fault levels has been accepted by the switchgear designer, with the result that, from consideration only of available switchgear, it is no longer necessary to subdivide the network or introduce artificial reactance to reduce short-circuit levels, although other operating conditions or economic considerations may still make such arrangements desirable.

The raising of the breaking-capacity level of switchgear has been accompanied by a reduction of about 60% in the total break time, which has been achieved by continuous research resulting in the shortening of both arcing time and mechanical break time. Modern circuit-breakers are approaching the goal of a three-cycle total break time, which includes at least one half-cycle of arcing—the minimum necessary to avoid undue current suppression. This improvement in total break time has been still further reinforced by constant development and progress in high-speed protective equipment, and, as a result, the stability of interconnected systems has improved despite their increased capacity. This steady progress in performance has been accompanied by a marked drop in the volume per kilovolt-ampere breaking capacity, the volume required at all voltage ratings having been more than halved over the last 25 years.

The fundamentals of the operation of air-blast circuit-breakers were established initially in this country, but their commercial application did not arise until the middle of 1930, by which time they and small-oil-volume circuit-breakers were in extensive use on the Continent.

Whilst these excellent designs have taken their rightful place in certain ratings and applications, they have by no means completely displaced the traditional oil circuit-breaker. In fact, as a result of further recent oil-circuit-breaker development, even in the very-high-voltage field the anticipated complete swing-over to air-blast circuit-breakers has not taken place.

The testing of switchgear has been given the greatest possible attention, and this country has achieved a leading position in the world, not only in respect of the number of testing stations in operation, but through the Association of Short-Circuit Testing Authorities (A.S.T.A.) it has set up a code of testing and certification which has no equal in the world and which sets a hallmark on British switchgear.

Future Load Growth

Little doubt remains in the minds of those primarily concerned as to the apparently insatiable rise in power demand in the

future, and the 6–7% increase per annum for this country is universally accepted, at least as a minimum. The extremely complicated civilization in which we live appears to have at least one common basis of thought—the desire to improve the standard of living of all its constituent members. It is difficult to define exactly what is meant by "standard of living," but by common consent it embraces the improvement in living conditions, hygiene, education and the ultimate reduction in the man-hours of productive work required to be performed by the people.

The importance of electrical energy in determining the standard of living is very marked, an increase in energy consumption *per capita* being reflected in increased standards of living due to the ability of electricity to reduce the man-hours necessary to produce the same amount of work. In so doing, however, it creates additional problems in that the members of the allegedly civilized races appear no longer capable of enjoying and using leisure hours in the simple and unaided sense, but demand the introduction of artificial stimulants in ever-increasing numbers, nearly all of which, either as a whole or in part, throw their impact back on to the electrical industry. Thus one has, in effect, a closed-loop system of ever-increasing intensity—the more abundant use of electricity producing greater leisure, which, in turn, produces an ever-growing demand for the "leisure consuming" devices which, in their turn, demand greater electrical energy. In hours of relaxation the aid of such "leisure consuming" devices as radio and television is being even more zealously sought, again creating expanded demand of no mean magnitude for electrical energy. In the home itself, the greater use of electricity in room heating, water heating, cleaning, etc., has enabled the housewife deservedly to enjoy greater leisure hours, which she employs in consuming more electrical energy.

Future Methods of Generation

No one can doubt that the future will lay heavy demands upon the electrical manufacturing industry, but the pattern of such demand may well vary as the full impact of present research crystallizes into material fact.

Perhaps the most significant trend which seems to be emerging is the prospect of applying some brake to the process of attrition, upon which the world embarked about 200 years ago. Quite obviously such a significant change cannot occur suddenly and does not mean the death of the coal industry, but it may well mean that it is no longer necessary to match the rate of electrical energy demand with correspondingly increased coal supply.

It is surprising to realize that, despite the disclaimers of a year or so ago, the most important contribution to this change will come from nuclear energy in the comparatively short space of the next ten years. The bold and imaginative programme described in the Government's White Paper of the 15th February, 1955, covers, at a cost of £300 million, the building of 12 nuclear stations with a capacity of 1 500–2 000 MW. In addition, the Atomic Energy Authority is constructing three additional stations, each of 100 MW capacity, to be operating by 1959. By 1965 the contribution of nuclear-energy stations will be of the order of 25% of the annual new-plant requirement, whilst by 1975 it is anticipated that about 20–25% of the total generating capacity of this country will be obtained from nuclear stations.

Whilst the early stations will rely on uranium as a fuel and will, in addition to heat, produce plutonium, the prospect of fast breeder reactors using pure, or nearly pure, fissile material and producing not only heat but more fissile material than is consumed opens up tremendous possibilities which, if carried to their logical conclusion, may well create a surplus of plutonium. Operating efficiencies of nuclear plant will, of course, improve as the new problems they create are attacked and solved, and here the probable direct use of the fissile material as a liquid may make an important contribution.

The recent development in the United States of barrier-layer photo-voltaic cells may prove a valuable contribution to the solution of the fascinating problem of utilizing solar energy.

A paper* was recently presented to The Institution supporting the view that the contribution which wind could make to power production, while certainly limited, is much greater than is generally believed.

Considerable interest has again been focused on pumped storage schemes whereby water is pumped electrically to a higher level during off-peak periods of electrical demand and used to drive hydro-electric generators for the supply of energy during peak-load periods. The C.E.A. is proposing to install in North Wales, subject to the necessary consents being granted, a 300 MW station working on this principle.

Nearly 200 years ago the world learnt to use the new sources of power opened up by the inventions of James Watt, and now, once more, we stand on the threshold of new discoveries which indicate that the future source of power lies in the conversion of matter into energy. The nuclear reactor is the first practical attempt, and in the more distant future, it may be augmented by the greater use of power derived from natural sources.

We have become acutely conscious of the "coal gap," i.e. the increasing difference between the amount of coal which can be produced and the demand for such coal in the foreseeable future. That this "gap" is not confined to coal is not so generally appreciated, and much research has been undertaken in attempts to assess the ability of the world to meet the future demands for economic energy. The problem is primarily based on economics —the potential reserves of the world's coal and oil fields are of academic interest only. What is relevant is the amount of fuel, be it coal, oil or gas, which can be delivered to the energy-producing sites at a cost which allows the energy to be produced at an economic price. Taking into account the increase in rate of world population and the industrialization of the world's present under-developed territories, it has been shown that the consumption of fossil fuels will rise to such a figure as to reduce the reserves to something of the order of one hundred years before the close of this century. The fact that we are, therefore, about two-thirds of the way through the era of fossil fuels, is complete justification for the attention now being paid to the problem of nuclear energy, since the estimated economically recoverable reserves of uranium and thorium alone, assuming a conversion factor of only 20%, are at least ten times greater than the remaining economically available conventional fuel sources. If, in addition, the possibilities of fast breeder reactors are taken into account, it would seem that nuclear fission will provide one of the early answers to a future plentiful supply of energy fuel.

Technical Recruitment

It would seem that the danger to the future of our industry lies not in a material shortage but in a human shortage of technical brains. Despite the great attention which has been given to this problem by government, industry and The Institution, the short-term future prospects are not encouraging. The number of full-time students attending universities and university colleges, who were reading for degrees or diplomas or were engaged on university research or equivalent advanced work, is showing a downward trend and in 1954 totalled about 80 000.

The electrical industry is primarily interested in the subject groups defined as "technology" and "pure science." Whilst practically all the technologists enter industry, no figures are available to show the proportion of those possessing pure-science

* GOLDING, E. W.: "Electrical Energy from the Wind," *Proceedings I.E.E.*, Paper No. 1727 S, November, 1954 (102 A, p. 677).

egrees who do likewise. On the basis that this figure is 50%, the probable number from which the whole of industry can draw for its higher trained technical recruitment is about 18 000. It must be realized that this pool serves the whole of industry, of which electrical engineering is only part.

Industry, however, is primarily concerned with results, and both the total number of degrees and diplomas obtained by full-time students at the universities and university colleges, and the total number of degrees and diplomas obtained in pure science and technology, show a slight drop. Again, on the assumption that all those possessing degrees or diplomas in technology, and ?0% of those possessing pure-science degrees or diplomas, enter industry, the probable recruitment to industry is represented by about 6 000 per annum, which, for the last four years, instead of showing a necessary increase has unfortunately remained almost constant. As a result of recent surveys it would appear that, at the present time, there is a discrepancy of 30% between the "demand" and "supply" of graduates in pure science and engineering.

In respect of the Higher and Ordinary National certificates, the position, although not satisfactory, is considerably better than that of the graduate class.

It is the belief of those primarily concerned that this problem of technical training, whilst demanding full, active and imaginative action at government level, will, in fact, be solved mainly by the efforts of industry itself by the introduction of extensive schemes for advanced training, designed to attract suitable candidates to the industry. This responsibility has already been accepted by the electrical manufacturing industry, and the major firms, at least, are already committed to large-scale and costly schemes primarily based on what is known as "the sandwich course," as a result of which, periods of practical training in industry are interleaved with academic training designed to produce the equivalent of pass-degree standard over a period of 5 years. It must be appreciated, however, that taking cognizance of National Service, such schemes cannot be of any benefit for seven years.

A helpful factor is the increase of the birth rate in the immediate post-War years, which is already having an effect and should reach its peak in 1960. It is confidently expected that more intensive propaganda, of which the recent film "Inquiring Mind" is an excellent example, will increase the number of boys interested in science.

Consideration of the future requirements of human direction spotlights in high relief the present attention which is being paid to so-called "automation," which has been defined as "the operation, control and scrutiny of machines by other machines in place of the human brain." Such a transitional mechanical process has, in fact, been proceeding for nearly 200 years. With the advent of electronic devices, however, the pace has suddenly accelerated, since electronic automation allows the range of operations of the machine to be considerably extended and made more flexible without mechanical change to the machine itself. It is not unnatural, therefore, that in some ill-informed quarters a feeling of fear and distrust has been created. In the necessity to increase productivity and remain competitive with the rest of the world, this coming technological revolution is inevitable and must be accepted and encouraged. The fear that the adoption of automation will reduce human beings to the level of robots and increase unemployment is unfounded. On the contrary, the adoption of modern methods, besides being the very essence of our continued survival, must have the ultimate effect of increasing the level of, and the demand for, human brains.

The Address attempts to sketch, in bare outline, the progress made in the heavy electrical manufacturing industry during the last half century, and it emphasizes the fact that the rate of such progress is accelerating, thus proving that we are still approaching the electrical age.

It is this challenge of the electrical age still to come which faces the young and future members of both the electrical manufacturing industry and The Institution, and one need have no fear of their ability successfully to meet this challenge and overcome the many and varied problems involved. They will carry the heavy responsibility for seeing that the results of future electrical research and development are directed towards the salvation of mankind, and not its ultimate destruction.

Abstract No. 1973 U
Feb. 1956

UTILIZATION SECTION: CHAIRMAN'S ADDRESS

By D. B. HOGG, M.B.E., T.D., Member.

"THE OPPORTUNITIES, RESPONSIBILITIES AND RECRUITMENT OF PROFESSIONAL ELECTRICAL ENGINEERS IN INDUSTRIES OTHER THAN THE ELECTRICAL INDUSTRIES"

(ABSTRACT *of Address delivered* 13*th October*, 1955.)

Introduction

As "all Gaul is divided into three parts," so for the purpose of what I have to say I have arbitrarily divided the industries employing electrical men into three groups, namely the electrical supply, the manufacture of electrical equipment with which is included consulting and contracting, and lastly the user industries, who are customers of the first two groups.

During the preparation of this Address three papers* on the general subject "The Electrical Industry as a Career" were read to the British Electrical Power Convention at Brighton this year, and grateful acknowledgment is made to the helpful ideas contained in them. What I am about to say may perhaps stimulate someone to write the missing fourth paper on "Electrical Engineering in General Industry as a Career."

User Industries

It is illuminating to contemplate a list of the various trades and industries of this country. The field covered is very wide. Nearly everything we eat, wear and use comes from one or other, and the roots of some go back to the dawn of history.

The following few are culled from the Ministry of Labour Gazette and have been chosen because they contain manufacturing units large enough to employ one or more professional electrical engineers, it having been stated that 80% of all works in Great Britain employ less than 100 persons, and it is thought that only in exceptional cases would one of these be an electrical man of professional status.

The trades or industries chosen are as follows:

Coal mining.
Quarrying.
Brick making.
China and earthenware (where electric kilns are used).
Glass making.
Cement making.
Blast furnaces.
Iron and steel melting and rolling.
Iron foundries.
Tin-plate manufacture.
Steel sheet.
Iron and steel tubes.
Non-ferrous metals, smelting, rolling and shaping.
Tools (machine).
Textiles (cotton, woollen, jute, rayon and other fibres).
Boots and shoes.
Cocoa and chocolate.
Tobacco manufacture.
Other food processing in large units.
Gas.
Water.
Theatres, cinemas, etc.
Coke ovens and by-product works.
Chemicals and dyes.
Explosives.
Paints and varnish.
Soap, candles, polishes, ink, matches, etc.
Mineral oil refining, greases, etc.
Ship building and repairing.
Marine engineering.
Boilers and boiler-house plant.
Textile machinery.
Ordnance and small arms.
Constructional engineering.
Vehicle manufacture.
Aircraft manufacture.
Locomotive manufacture.
Carpet making.
Grain milling, bread and flour making.
Paper making.
Printing.
Cardboard-box making.
Civil engineering and building (large units).
Railways and tramways.
Hotel and catering (large scale).

* "The Electricity Supply Industry," by Sir Henry Self.
"The Manufacturing Industry," by S. E. Goodall.
"The Installation Contracting Industry," by R. A. Marryat.

Mr. Hogg is with Imperial Chemical Industries, Ltd.

It is interesting to note that the largest industry in Britain, i.e. the largest from the point of view of numbers, namely agriculture, is not included above. It seems that there are no aggregates large enough to require the whole-time services of electrical men.

As to how many electrical engineers are employed in "user industries" and how they are distributed among them, it is regretted that no useful information has been found. Even the records of The Institution contain no up-to-date classification by industries because members moving from one works or industry to another seldom mention what their new job is. However, the report for the 83rd Annual General Meeting gives these figures for the year ending 31st March, 1955:

Total number of Corporate Members	Over 20 000
Numbers of all classes in the four specialized sections	16 000
Numbers of all classes in the Utilization Section	Over 4 000

Of course the last group includes some who are in the electricity supply and manufacturing industries, and it is also known that many corporate members do not join any specialized Section. A guess that there may be up to 10 000 professional electrical engineers employed in "user industries" in this country, therefore, may not be very wide of the mark.

Opportunities

The young man about to start a career in electrical engineering or one newly qualified from university—or indeed an older man looking for wider horizons and promotion—is apt to think that electrical engineering is to be found only in the supply and electrical manufacturing industries. There is no doubt that these are the main streams in the electrical world, but unless the aspirant is set on becoming and remaining a specialist, or at least intends to devote himself to a comparatively narrow field, he would do well to consider the wider world outside where electrical engineering is only an adjunct to the business of making and selling something quite different or providing some service, such as transport, gas, or water. Even in these industries it is possible to specialize to some extent, but all the time a man can rub shoulders with others of professional status who are engaged in other occupations having differing outlooks and viewpoints and thus he can more easily become a whole man, or shall we say an "engineer" rather than simply an electrical engineer.

It may be true that only a small proportion of "user industries" are large enough to do their own consulting, run their own electrical design and construction sections, and have research departments in addition to doing their usual operation and maintenance, but a fair number employ civil, mechanical, as well as electrical engineers and have in addition specialists such as chemists, metallurgists or physicists who are necessary properly to control and improve the product being made.

Let us look at the organization of some imaginary companies to see what scope there is for electrical engineers to rise to the highest posts. None of these is the "family tree" of an actual

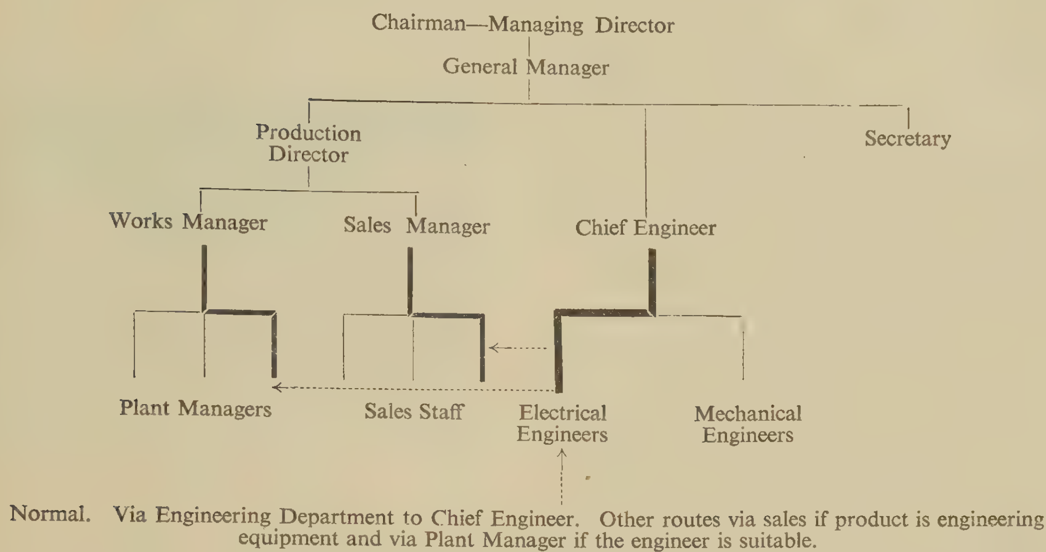

Fig. 1A.—Medium-size company (using consultants for extensions): Routes for promotion of electrical engineers.
Note.—Other departments left out for sake of clarity in diagram.

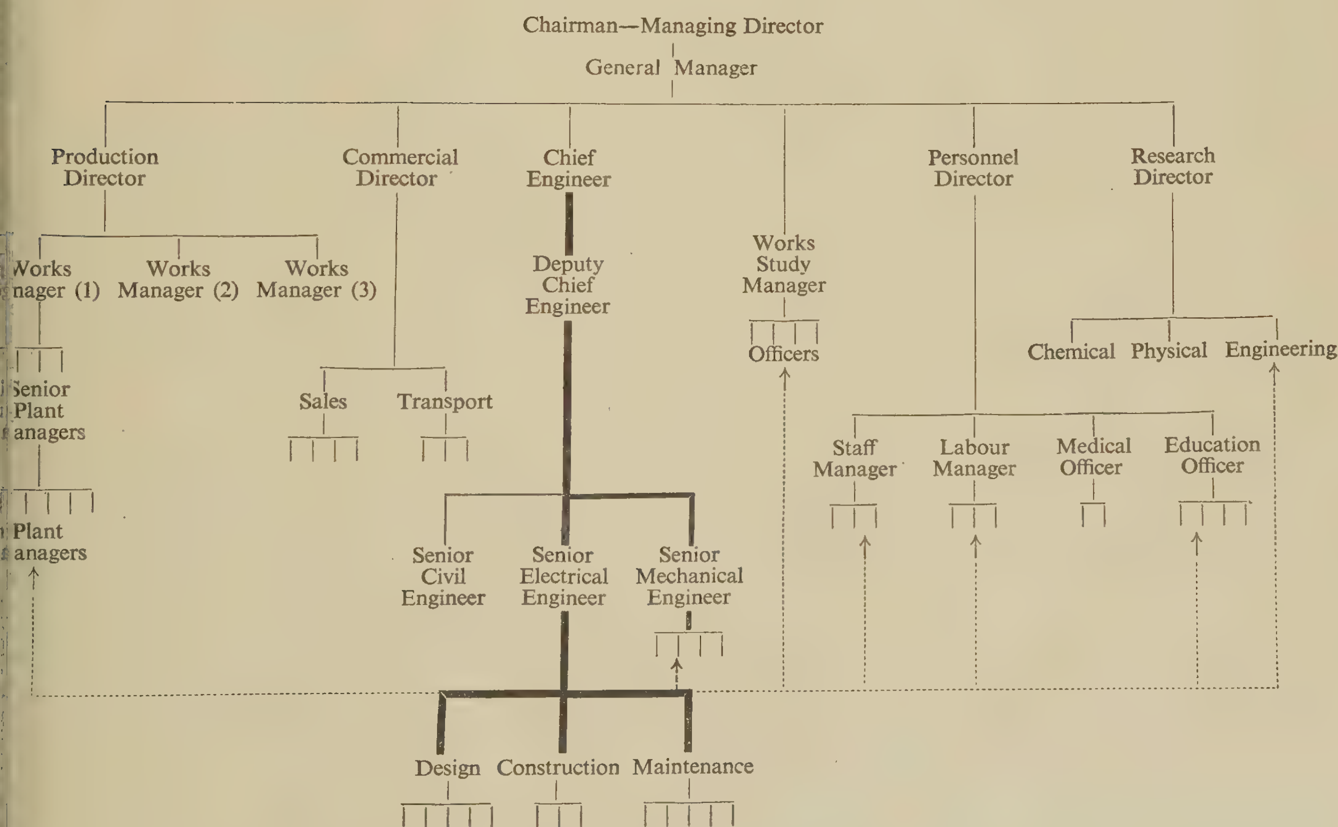

Fig. 1B.—Large-size company (undertaking its own design and erection).
Other departments, such as Accounting, Secretarial, etc., have been excluded for the sake of clarity.

company but they are believed to be fairly close to what might be expected in a medium size and in a very large organization (see Figs. 1A and 1B).

It will be appreciated that no two companies are organized exactly alike, nor are the responsibilities of their engineering sections alike. Some industries, such as iron and steel, shipbuilding and plant manufacture, for example, may have recruited many of their production managers from the ranks of engineers, while some other trades use engineers solely for repair and maintenance, and there are all stages between these, depending on what goods are produced and the traditions of the business.

A young electrical engineer coming into the larger concerns can, if he wishes and is interested, find several ladders for promotion. He will probably start in the engineering department on either the design, construction or maintenance section. He may elect, or be found more suitable, to make a career in one of these, perhaps moving for a few years from one type of work to another until he finds his niche, and if he has it in him and vacancies occur at the right time, he may in course of time reach the dignity of chief electrical engineer or its equivalent.

On the other hand he could, in some industries, be moved on to the production side, climbing from plant manager through works manager to production director. Or he could try work study or sales if the product is of an engineering nature. Promotion to the higher executive or administrative posts will depend on the man, but with several routes it need not entail waiting so long for opportunities as sometimes proves to be the case with a career in purely electrical engineering.

The idea of becoming a mechanical engineer, a salesman, a plant manager or work-study officer may strike some electrical engineers with horror. Why should he spend all those years of concentrated study and training only to throw it all away? Well, what does he want from life anyway? A job which requires one's full effort, in which there is true satisfaction in doing it, which is adequately paid and has good chances of advancement to greater responsibility is what most of us are really after. Why then worry what label is attached to it, whether electrical engineer or something else? The basic scientific knowledge and training to think acquired in college is never wasted if used in other walks of life.

In a number of large industries there are research departments with sections which deal with the materials used to build the plants. Guidance is given in the design stage as well as to the maintenance engineers on the materials best suited to withstand particular corrosive, high-temperature or high-pressure conditions. When a breakdown occurs, be it only a broken bolt, it is usual to call in the research department to examine the occurrence metallurgically, chemically and in other ways, and to suggest improvements in materials or techniques to prevent or minimize the danger of its happening again. Such work often saves great expense which would have occurred had the older method of trial and error, so well known in British engineering, been used. The few examples which follow may serve to illustrate this.

Case (i): Effects of "Arcing" on Alloy Steel from Brass Clamps

High-pressure gas for the production of a special material is conveyed in 13% chromium-steel pipes and is heated electrically by passing heavy electric currents through the pipes which are of appreciable resistance. Brass clamps are used to attach the supply cables. During routine examination of one of these pipes, "craters" were found; these were points where arcing had occurred between the brass clamps and the pipes. Although these craters appeared to be only superficial damage and were, therefore, at first disregarded by the operating staff, examination by the research department showed that the damage can be extreme serious as shown by Fig. 2, which is a section through one the craters. The extensive cracking in this case was due (*a*)

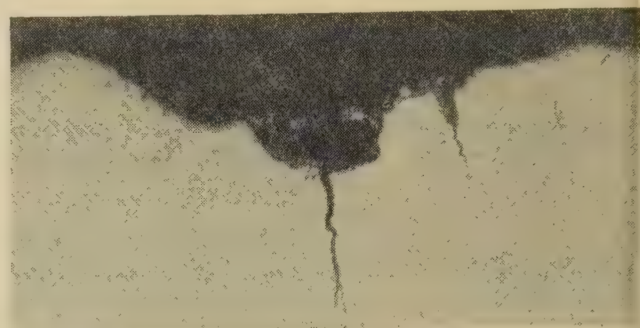

Fig. 2.—Effects of arcing on alloy steel from brass clamps; showing section through one of the craters.
Magnification: × 9.

intercrystalline penetration of the alloy steel by molten bra and (*b*) to thermal hardening.

The immediate action taken was the replacement of the bra clamps by steel ones together with thorough and regular insp tion to ensure that the electrode clamps were in intimate conta with the pipes.

Similar cracking was also found in a low-alloy steel compone where arcing had occurred between a copper electrode and t component.

Case (ii): Renovation of Electrical-Motor Shafts by Met Spraying

The slight wear experienced occasionally on motor shafts c be rectified by special metal spraying. Normally the surface be sprayed has to be either shot blasted or severely roughened order to key the sprayed metal to the base, and frequently t results are not satisfactory owing to lack of adequate adhesio Recent work by the materials research section of one firm sho that ordinary machined surfaces on shafts can be built up sat factorily by metal spraying if a thin sprayed coat of molybdenu is first applied, the final thickness required being obtained spraying a metal such as nickel on top of the molybdenum. It claimed that some alloying takes place between the molybdenu and the steel surface, giving superior adhesion compared wi previous spraying techniques.

Case (iii): Metallurgical Proof that a Heating Element had fail by Fusion and not by Mechanical Damage

A new nickel-alloy-wire heating element failed shortly after was installed in service, and it was essential to know whether t failure was due to mechanical reasons or fusion. The micr structure of a longitudinal section of the wire after suitab polishing and etching revealed under the microscope conclus proof that fusion was the cause of failure. This was shown the fact that partial or complete fusion of the nickel-rich so solution, followed by fairly rapid cooling (as would be the ca in a wire element) produces a structural change which is eas visible.

The Cracking of Brass Armouring on a Gas-Pressurized 66 Cable in a Tunnel

Parts of the high-zinc-content (65 : 35) brass armouring a gas-pressurized cable had cracked after exposure to salt wa

following local damage of the outer rubber sheathing. Examination showed the cracking to be due to stress corrosion, the type of cracking being intercrystalline (see Fig. 3). Experiments in the

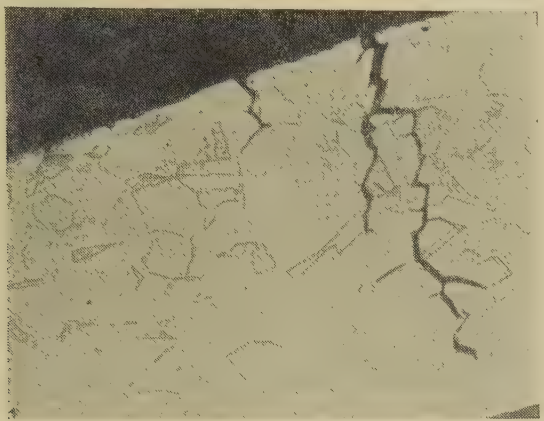

Fig. 3.—The cracking of brass armouring on a gas-pressurized 66kV cable in a tunnel.
Magnification: × 150.

laboratory indicated that the *applied* stresses produced in the brass by the internal pressure of the gas in the cable were probably more responsible for the stress-component part of the mechanism than the *internal* stresses in the cold-rolled brass-strip armouring. The corrodent was, of course, the small amount of salt water. It is known that high-zinc-content brasses are very susceptible to stress corrosion, and some material far less susceptible was obviously desirable. The material successfully used as a replacement was 90 : 10 copper–zinc brass, the higher copper content giving increased resistance to stress corrosion.

The point being made is that the problems in "other industries" cover such a wide field that the electrical engineer who is fortunate enough to work in any of the large ones is encouraged to explore other engineering and scientific fields, and in the course of time attains a useful knowledge of many things other than those of a purely electrical nature, which is good for him and for industry generally. While he is unlikely to become expert in these other fields he will know what is being done and where to go for information.

Many trades have an ancient lineage, and an engineer "worth his salt" will delve not only into the modern ways of manufacture of his company's products, so that he is better fitted to put forward constructive ideas for improvements, but also into the historical processes where he is apt to find all kinds of queer practices, some of which may derive from ancient cults and religious influences. There is still a great deal of *mystique* and tradition about British industry, some of it out of date and a drag on progress. The well-educated and intelligent engineer looking at an old trade from the fresh angle of his training and scientific background should be able to sort the wheat of inherited skills and know-how from the chaff of dead custom and inertia, and if he goes about it with tact and nous, persuade his employers to use modern science and engineering to the betterment of the product and enrichment of everybody concerned.

Responsibilities

There is a saying attributed to Sir Ewart Smith that "responsibility is taken, not given." It is demonstrably true that the engineer who readily and consistently takes responsibility is earmarked for promotion.

It is not unusual to find engineers complaining that they are not given the degree of responsibility they consider their due and often they couple with this, dismal stories of how their pet schemes are turned down by accountants and other non-technical directors who refuse money for necessary repairs or improvements. It seldom occurs to them that if they are employed by a go-ahead company the fault lies in themselves, and that if the company is of another sort it is high time they changed their employment. It is their fault because they have failed to produce a simple clearly written report explaining why they wish to spend the money, giving costed alternatives and showing which scheme gives an adequate return for the capital involved. In short they consider that they should be given responsibility to spend money because they are qualified engineers. Beautiful technical solutions to engineering problems are alone seldom sufficient inducement to hard-headed directors to spend shareholders' money.

One of the most rewarding responsibilities of engineers lies in the field of labour relations. To get the best out of men, be they staff or payroll, requires careful study and much practice. The better the education and the quicker the brain of the engineer, the more need he has of getting behind the thinking processes of his people and seeing that they understand the reasons for the company's rules and regulations, and why they must do this and not do that, and why plant is built and run the way it is, and so forth. The engineer who can carry his tradesmen and labourers with him has a minimum of inter-Union friction, and the engineer who co-operates fully with his fellow engineers is worth much to his firm.

Some large companies seldom employ consultants for their extensions and it is the responsibility of their engineers to produce the most economical solutions when designing and building new works and alterations to existing ones. Here the trained engineer who keeps up to date with world practice has his opportunity to lead the field, and it is his job to weigh up and advise on the choice between repeating well-tried and efficient plant and methods or advancing towards higher efficiencies and new techniques, maybe with some risk of prolonged development troubles, in search of new markets, cheaper products and enhanced profits.

In outlining in greater detail some of the responsibilities which fall to the lot of electrical man, I will first consider the design section: Here he will have to collaborate with the supply authority regarding the provision of an adequate power supply, and negotiate tariffs. He must find out about the prospective fault current so as to be in a position to purchase switchgear of adequate fault capacity. He may have to plan a private generating station. He will have to plan his internal network to give the works adequate alternative sources of supply in the event of partial failures on the factory main distribution system.

He must find out for what degree of corrosion his motors, wiring, lighting fittings and other equipment should be designed, and also whether explosive hazards will be encountered. He must be thoroughly familiar with the Factories Acts, the Electricity Regulations and all relevant statutory instruments. It goes without saying that he must know The Institution's Wiring Regulations.

He should try to standardize equipment and wiring techniques to prevent overstocking his stores and the following of the latest fashions for the sake of novelty. He has to prepare estimates, write reports (and sometimes attend outside committees), and correspond with manufacturers, other departments and outside bodies.

He should learn how the manufacturing plant in new works or extensions is intended to work, and consider and advise on better methods of control of the plant and whether automatic control will pay.

Next I will consider the construction engineer, whose responsibilities are very different. He works from prepared plans and material lists, but his main duty is to get the plant built to programme at an economical cost while fitting his work in with the civil and mechanical sides. Although he is usually the last into a building, he must not be the cause of the plant starting late. It often happens that the best and most economical order of erection of the electrical gear will clash badly with the mechanical programme, and he must learn to co-operate—and usually give way, for, as a rough guide, his share of the capital will be less than 10%.

One of his main responsibilities is to work his labour economically and prevent friction—both internally and with other trades. He, too, must write reports, collect costs, check contractors' bills, and undertake a host of other office jobs.

The maintenance engineer may have to check all his plant and carry out acceptance tests. He should compile schedules of spares and order them, steering a difficult course between the Scylla of locked-up idle capital for spares bought "just in case" and the Charybdis of an angry works manager with production held up because of the lack of some vital part with a long delivery period. He should list all items of equipment and prepare detailed work schedules for their routine overhaul. He should plan his maintenance months ahead, working out his requirements of spares and consumable stores, and he should educate his production management to realize that laying off plant at set intervals for planned maintenance is economical and will cut down the incidence of unexpected breakdowns with their high cost in lost production. With this well done he can plan his labour force and not have a surplus for which he has to find uneconomical work. He has to prepare routine reports, check costs and do routine writing concerning leave slips, pay adjustments, etc.

All the above, which are only a summary of perhaps the more important items, are, of course, the lot of engineers in the supply and manufacturing industries also, but it is probable that it is only in "user industries" that one engineer has so many different duties to undertake.

Recruitment

In my young days only a few firms in "user industries" took schoolboys and trained them up to the standing of professional engineers; most of them recruited their staff from electrical manufacturers, or sometimes promoted outstanding tradesmen to staff posts. The majority of electrical engineers obtained from manufacturers or contracting firms were public school or grammar school boys who had served a 5-year apprenticeship, attended part-time courses at a university or technical college, passed the Institution examination and become Corporate Members. Since those days the proportion of university graduates coming into industry has risen greatly, and many of these have found their way into "user industries."

For many years a few of the larger firms have made special efforts to recruit university graduates and train them in their own works. There is no doubt that, taken as a whole, although these men may never have a detailed and intimate knowledge of how to rewind a motor or be able to dispute from personal experience with cable jointers, their fundamental knowledge and training to think carries them more readily into the higher-paid posts, and at an earlier age. They also prove more adaptable and less inclined slavishly to follow previous practice (perhaps because they have none) and can the more readily be given jobs to do which are not essentially electrical. Nevertheless there are still ample opportunities for men who have been trained in other ways; practical experience has a high market value, and good men without degrees will continue to be promoted. There is no question in my mind that a greatly increased intake of graduate engineers, civil, mechanical and electrical, into all the trades and industries of this country is essential if we are not to fall behind our competitors and to have to reduce our standard of living.

Conclusion

There are many trades in this country having large enough units to employ electrical engineers of professional status. Although specialization in electrical work is not easy in these jobs, there are opportunities for engineers to acquire all-round experience, to become whole men and to rub shoulders with graduates in other walks of life, and it is electrical men with all-round experience who are most in demand. The financial rewards are at least as good, and often better, than in the other two spheres. There is plenty of room to-day for good men, and especially young men with good honours degrees.

Finally, I would state that the views I have expressed are my own, and are not necessarily those of any particular company or companies.

CENTRE, SUB-CENTRE AND GROUP CHAIRMEN'S ADDRESSES

Abstract No. 1977
Feb. 1956

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By F. BARRELL, M.I.Mech.E., Member.

"THE DEVELOPMENT OF POWER-STATION CONSTRUCTION IN LEEDS AND THE SURROUNDING AREA"

(ABSTRACT *of Address delivered at* LEEDS, *4th October*, 1955.)

The opportunity is taken to deal with the specialized branch in which I am engaged and to give attention to matters of local interest. The subject has not been dealt with previously by a North Midland Centre Chairman.

In July, 1891, the Yorkshire House to House Electricity Co., Ltd., was granted a provisional order to establish an electricity undertaking in the City of Leeds. The supply began at the Whitehall Road Power Station on the 1st May, 1893, with a generating-plant capacity of 0·25 MW. The Leeds Corporation purchased the undertaking as from the 1st October, 1898. The generating capacity was then 2·4 MW. Almost immediately afterwards, construction commenced of a new power station adjoining the electricity works, and ultimately this accommodated 37 MW of plant. In 1912 a portion of the existing works was rebuilt and extended, and this section finally housed plant having a total capacity of 45 MW.

The 1909 and 1919 Acts provided small changes in policy and supervision, but had little effect on the development of the undertaking. The 1926 Act had a major effect on power-station construction, in that it permitted larger units to be constructed and reduced the number of undertakings and companies that were permitted to lay down new power stations.

The idea of a Kirkstall power station had developed prior to the 1926 Act, but this Act, being a scheme of national generation, led to the installation of large-sized turbine units in this station. Energy was first supplied from the station into the distribution system on the 8th October, 1930. Its present capacity of 200 MW was reached in December, 1947.

Following the passing of the 1926 Act, the Leeds undertaking was in a happy position, having two selected power stations, and was able to obtain very preferential price rates from the Central Electricity Board, because of Section 13 of the 1926 Act, which permitted costs of electricity to be based on the ability to generate electricity cheaply. The 1947 Act broke down this facility, and created a national generating authority which paved the way for generation of electricity in large power stations located in areas where fuel was more plentiful and cheaper.

The growth of the electrical load in the Leeds area has followed a reasonably constant mathematical law since the inception of electricity supply, apart from the disturbances during the wars and early post-war periods. In general terms, the rate of growth was equivalent to doubling the demand every ten years, and it set the pattern for the extension and construction of power stations.

The design, development and construction of these power stations entailed the gradual growth of a specialized department within the Leeds Electricity Undertaking, and consequently, with the nationalization of the industry in 1948, this department became the nucleus of a larger organization, for the construction of power stations in a wide area of the Yorkshire Division of the Electricity Authority. Details of this construction organization were given in the Address.

The location of suitable sites for new plant construction is a very difficult problem, and the main target is a site which will give the most economical supply of electricity to the consumers. The many requirements that need to be satisfied include:

(*a*) Easy access to coal supplies.
(*b*) Proximity to the area of demand for electricity.
(*c*) Location in relation to built-up areas in order to disperse vapour, grit and waste gases without nuisance.
(*d*) Suitability of land for foundations, freedom from mining subsidence and avoidance of sterilization of existing coal seams.
(*e*) Freedom from flooding.
(*f*) Areas near station for disposal of ash and dust.
(*g*) Amenities, including the need to avoid green belts under the Town and Country Planning Acts of 1932 and 1947, and to avoid close proximity to ancient monuments and shrines.
(*h*) Well remote from airfields.
(*j*) Availability of housing and other services for the adequate housing of construction personnel and operatives.
(*k*) Abundant water supplies.

The problem of ample cooling water is usually the most acute, and this requirement has influenced the location of recently constructed power stations more than any other.

The construction of power stations has been proceeding for over 60 years, and the most valuable sites have now been used, but improvements in electrical transmission have made the siting of power stations more flexible. In view of the high transport and transmission costs, however, it is of economic value to make the very best use of the cooling effect of all available water supplies, if this helps to reduce the distance of transport of coal, and the transmission of the electrical output of the power station.

This principle was applied in designing and locating the Skelton Grange "A" power station. The chief source of cooling is the River Aire, which has a flow ranging from 2000 million gallons per day during extreme floods, to a minimum of 33 million gallons per day. This minimum flow is largely effluent from the sewage works on the upstream side of Leeds, and excludes the sewage effluent from Leeds.

The River Aire through Leeds is used in part as a navigation canal, and unfortunately this canal leaves the river upstream from the Skelton Grange power station, at the start of a long section of canal with five locks. The make-up water required by this long section is not less than 20 million gallons per day, i.e. a high proportion of the minimum river flow, and this would be lost to the power station, particularly as the canal make-up is dependent on the transit of canal boats through locks, and the rate of flow of make-up is at a maximum in the day time, and can exceed the minimum flow of the river. This detrimental and disturbing factor was changed to an advantage at the power station by the provision of a system of recirculation of water between the canal

Mr. Barrell is with the Central Electricity Authority (Yorkshire Division).

and the river. In simple terms, this consists of pumping water from the river to the canal at a point nearly two miles downstream from the discharge from the station, and permitting the water to return along the canal in an upstream direction, and over a spillway into the river above the power-station intake. Ninety million gallons of water per day can be pumped into the canal, part of which is recirculated, and, in addition, the 20 million gallons of water coming downstream, and normally used as canal make-up, are available for cooling the power station. The recirculating system, extending nearly two miles downstream, gives the power station the advantage of downstream cooling.

The power station is located adjacent to the Leeds sewage works, and the whole of its effluent can be pumped into the power-station cooling system. In addition, 10 million gallons per day can be pumped back from the power station to the sewage works, thus using the 36 acres of bacteria beds as a cooling medium. The sewage-works system provides a total flow of 30 million gallons per day. Cooling towers supplement up to half of the station cooling requirements, and are only used fully during periods of high load and low river flow.

The total flow of cooling water for the 360 MW station is 372 million gallons per day, and the heat dissipated is approximately 6 200 B.Th.U./kWh generated.

The Skelton Grange power station has been in use since 1951, and during the first year of operation was the most efficient station of its class in the country. It has also taken and held the lead for the lowest cost of production, but this is due in part to its favourable position in relation to the coalfields.

The use of rivers for cooling became more complicated when the River Boards were granted certain regulatory authority over the discharge into rivers by the Rivers (Prevention of Pollution) Act, 1951. This development led to a public inquiry in connection with the Wakefield "B" power station. The result was that the Electricity Authority and the River Board agreed to an interim trial period, when detailed observations would be made to ascertain the effect of the discharge of warm water on river conditions. The results will be a national issue, and will need to be thoroughly analysed, carefully considered and debated before a final decision is made.

I have dealt with the background of power stations developed and constructed in the Leeds area, with particular emphasis on the cooling problem; and in order to look into the future possibilities of this area, it is necessary to view the national position.

There is no doubt that the electricity demand will steadily increase in keeping with the rising industrial production. The declared policy of the Government is to double the standard of living in 25 years' time. This is only possible by the medium of electricity, which would supply the domestic equipment and labour-saving devices to increase the standard of living, and, in addition, would largely supply the means of increasing production of our basic industries and factories. The contribution of electricity is therefore twofold.

The national requirements for increase in fuel for electricity generation over preceding years can be shown by the fact that in 1953–54 public supplies sent out 7·3% more electricity with 4·3% more coal. In 1954–55 11·9% more electricity was provided for 9·8% more coal. Oil is to be used in part to meet the increase, and agreements were made this year between the Authority and three of the major oil companies for oil to supply 14 new or existing power stations. Atomic power stations are now being planned, and details of Britain's programme of nuclear power are widely known. Over the next ten years or so the programme provides for a capacity of 1 500–2 000 MW at a total cost of about £300 million.

The effect of these sources of power which are alternatives to

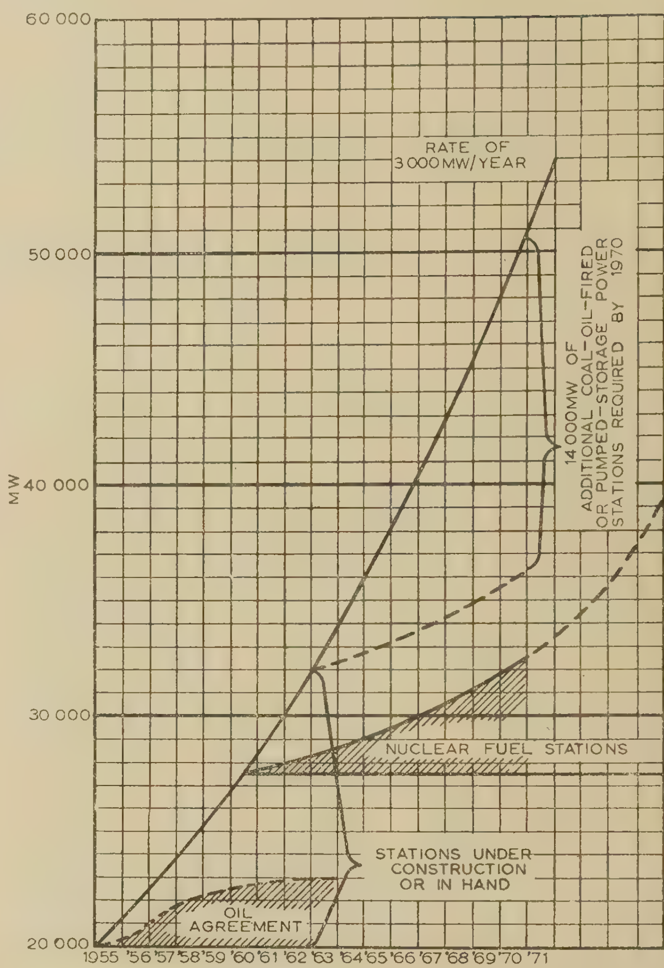

Fig. 1.—Trend of public electricity supply installed capacity in Great Britain.

coal is shown in Fig. 1, which gives the forecast of installed plant capacity to meet the probable demand for electricity until 1972. This chart illustrates the very rapid strides that will be necessary with atomic-power development, if this source of power is to meet the whole growth after 1975. A total capacity of 14 000 MW for the new stations in addition to the nuclear power stations appears to be required by 1970.

A few hydro-electric stations will possibly be installed, and there might be an exchange of power with other countries. In addition, existing power stations will have some plant replaced by more up-to-date units, but in general terms, these comparatively minor contributions to the requirements will take the place of existing low-efficiency plant.

It should be noted that the 14 000 MW capacity of new power stations required by 1970 can be coal- or oil-fired thermal stations or pumped storage. Pumped storage as a means of meeting the maximum demand is possible because of the lower load on the national system during the night time as compared with the day time. During the particular day of the peak load this year, the load factor, or ratio of average to peak demand, was about 70%. It is highly desirable that pumped-storage schemes should include some basic power contribution from nature, and not be 100% pumped-storage schemes, because their double conversion inefficiency plus water and electricity transmission losses would be a waste of fuel. This may not apply in the very distant future, if the basic cost of nuclear fuel becomes appreciably less than the

cost of coal. In the meantime, more energy storage could be done on the utilization side, which would have the additional advantage of saving on distribution losses and cabling.

I have given an outline of the national requirements of power, and therefore, returning to the local contribution to these requirements, it is unfortunate that there are no large-scale oil refineries in Yorkshire, and thus it is not economical to supply oil in bulk amount to this area. The atomic stations to be built initially will be remote from coalfields. Yorkshire's contribution to the required increase in output of electricity is therefore largely dependent on the output of the Yorkshire or nearby coalfields. In 1954, 43% of the country's output of deep-mined coal was produced by two Divisions of the National Coal Board in close proximity to this area.

Reference has been made to the siting of power stations being largely dependent on adequate cooling-water supplies, and thus it is of some importance that the main rivers flowing through these two main Divisions of the National Coal Board discharge within the boundaries of the Yorkshire Division of the Central Electricity Authority.

Of the 11 or more very large coal- or oil-fired power stations required in the period commencing 1962, economic conditions justify a few of these being located in the Yorkshire area.

There seems little doubt that the fuel requirements of the country during that period will cause great difficulties, and it cannot be stressed too strongly that more efficient utilization of heat must be vigorously applied. To build larger and more efficient power stations near coalfields is not only necessary to meet the increasing demands for electricity, but also to accelerate the process of replacement of inefficient power stations. Tremendous efforts have been made since the war to close gaps in our fuel and power resources, and these efforts must continue, particularly by the engineers concerned with improving coal-mining machines and techniques.

River cooling is desirable, because river works are usually cheaper than the equivalent works for cooling-tower schemes, and the turbine/condenser vacuum is improved with consequent higher efficiency and saving of fuel. The design of the cooling systems in power stations in recent years has been handicapped, because there has not been a clearly recognized standard of the permissible amount of heat that can be rejected to rivers. Limitations have been imposed which have led to inefficient use of fuel. It is therefore of national interest that Ministry investigations are now about to take place, arising from the Wakefield inquiry, and the arbiter will doubtless define a clear policy, giving the amount of heat that may be absorbed by rivers. This will give a balance between the amount of disturbance to present users and the future effect on the use of our fuel.

Fuel and cooling are the two main factors which will determine the choice of our future power stations in the next two decades, and as far as Yorkshire is concerned, there are still some natural resources in store, though not in abundance.

Abstract No. 1976
Feb. 1956

NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By A. H. KENYON, Member.

"POWER-SUPPLY DEVELOPMENTS IN THE NORTH-EASTERN AREA"

(ABSTRACT *of Address delivered at* NEWCASTLE UPON TYNE, 10*th October*, 1955.)

Introduction

We have heard a great deal in the last few years about the generating-plant programme, and also about the 275 kV Grid which is being used to provide additional interconnection capacity between the different Grid areas and the bulk transmission of power from new power stations in or near the coalfields. The continuous increase in demand for electricity is taken almost for granted, and I thought that it might be of interest if, in my Address, I attempted to examine the growth in the use of electricity so far as north-east England is concerned. Most of the figures which I shall use relate to the Area of the North Eastern Electricity Board, which covers the counties of Northumberland and Durham, the North Riding of Yorkshire, and a little of the East and West Ridings, including York and Harrogate.

This area is naturally regarded as one of the industrial areas of the country, although it includes a very large expanse of rural territory. The difference between this area and the average of the country as a whole can, perhaps, best be illustrated by the fact that in this area last year industry took 64% of the total number of kilowatt-hours sold, whereas the figure for the country as a whole was 51·5%.

The public supply of electricity in the north-eastern area dates from 1890. Darlington, Stockton and York obtained their Statutory Orders in that year, and Harrogate, Sunderland and Tynemouth received theirs in the following year. The Newcastle upon Tyne Electric Supply Company and the Newcastle and District Company were incorporated in 1889 and received their Orders in 1891. At that date the promotors of these two companies were thinking in terms of lighting only, and early records of the Newcastle upon Tyne Company show that its object was to supply electricity in the eastern half of Newcastle for 4 500 ten-candle-power lamps, of which 3 000 could be alight at one time. The plant to do this job consisted of two 75 kW generators, each driven by a Robey slow-speed steam engine.

By 1901, 3-phase alternating current at 5 500 volts was being distributed to industry on Tyneside. This was the first example in this country of 3-phase distribution in bulk, and seven years later every shipyard and engineering works in the supply company's area on the north bank of the Tyne was taking a supply for power purposes. I think it is true to say that in the early years of the century the supplies to domestic and commercial premises, apart from theatres, larger shops, etc., were regarded as being rather a nuisance. They had to be given because the Electricity Orders granted by the Board of Trade listed streets in which supply mains must be laid or the Order would be forfeited, and provision was made under which consumers could requisition a supply. Certainly, the supply authorities did not visualize the potential load which was waiting to be developed in the domestic and commercial field, although some of them were well aware of the industrial possibilities.

If was the falling off in the industrial demand in the slump after the First World War which set supply engineers thinking about the possibility of developing a load which would not be so subject to trade fluctuations.

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In 1923, two members of the North-Eastern Centre of the Institution, Messrs. H. A. Couves and W. F. T. Pinkney, visited America to find out what the supply undertakings there were doing about the development of the domestic and commercial load. They spent three months touring the country, visiting New York, Toronto, Chicago, San Francisco, Seattle, Cincinnati, Philadelphia and Boston. I would like to read you a short extract from a report which they made when they returned, because I feel that it will illustrate the point which I have been making about the lack of interest up to that time, in this country, in the development of the commercial and domestic load. They said:

We were very particularly impressed with the developments that have taken place in the supply of electricity for domestic purposes. This class of business appeared to us to be that upon which all the undertakings, to which we were introduced, concentrated their greatest efforts. As a consequence of this, we spent a very considerable time investigating the methods adopted for dealing with this class of business.

To illustrate the extent of these developments, each of the towns we visited, with the exception of Cincinnati and Boston, claimed to have connected to their systems at least 80% of the dwelling houses within their area of supply, and in the case of Seattle it was claimed that every house in the city was connected.

Of the total number of dwelling houses within the boundaries of Newcastle, probably not more than 10% are connected to the combined systems of the Newcastle Company and the District Company.

Another interesting comparison is the ratio of consumers to population. The average ratio of all the American undertakings under review is approximately one consumer to every six of population. The corresponding figure for Newcastle City is about one to 28, and according to the latest figure published by the Electricity Committee of the Glasgow Corporation, the ratio for Glasgow is approximately one to 20. We have quoted the Glasgow ratio as the electricity undertaking in that town is one of the most active and enterprising in Great Britain, and the figures assist to illustrate how very far advanced the domestic-supply business is in the case of American cities, as compared with our own.

That report was written in 1923, 34 years after supply was first available in Newcastle upon Tyne—one consumer to 28 people, and 10% of the houses connected. The figures for the North-Eastern Area at present are one consumer to 3·4 of the population and approximately 90% of the houses connected.

The way in which the balance of the load has changed during this period of 35 years from 1920 to 1955, can be seen from Table 1.

Table 1

PROPORTION OF TOTAL CONSUMPTION OF ELECTRICITY IN THE NORTH-EASTERN AREA

	Industry	Commercial premises	Domestic premises	Farming purposes	All traction	Public lighting
	%	%	%	%	%	%
1920	88·8	3·6	2·0	—	5·3	0·3
1930	82·3	6·0	6·2	—	4·6	0·9
1938	74·6	7·9	12·3	0·2	3·9	1·1
1945	76·5	6·3	14·0	0·25	2·65	0·3
1954–55	64·6	10·6	21·4	1·1	1·6	0·7

Industrial supplies, although now four times as large as they were in 1920, represent only 64% of the total load as compared with nearly 89% in 1920. On the other hand, sales to commercial premises now represent 10·6% compared with 3·6% in 1920, and sales to domestic premises have gone up since 1920 from 2% to 21·4%.

I will now review very briefly some of the different classes of load.

Mining

About 24% of the total amount of electricity sold in this area goes to collieries. As one would expect with an industry which generally works two coal-producing shifts every 24 hours, where there are large continuous ventilating loads and where pumping is mostly carried out at night, the annual load factor is high, varying usually somewhere between 45% and 50%, but in some instances it is as high as 66%. The increase in the number of kilowatt-hours sold last year was 6·3%, which is rather less than the average annual increase for other industrial supplies, but this is accounted for by the fact that the electrification of the bulk of the motive-power plant at the pits was carried out some time ago. Increases depend mainly on the development of new pits, the replacement of larger steam-driven plant such as winders, air compressors and ventilating fans, the installation of coal-preparation plants and the further development of intensive mechanized mining in the existing pits.

One branch of mining to which I would like to refer for a moment is the development of opencast mining by machinery supplied from the Electricity Board's system. Until about the end of the war, the excavators used in the area on opencast mining were comparatively small Diesel-engine-driven machines, the coal deposits worked being, generally speaking, close to the surface. In order to work the deeper deposits, however, larger machines had to be used, and early in 1949 the first large drag-line excavator was installed at the Ewart Hill site near Bedlington in Northumberland. This machine was of American construction, and, at the time, was the largest drag-line excavator outside America. Its working weight was approximately 1 150 tons and it was equipped with a 25 yd^3 bucket (pay load about 34 tons) and a 185 ft jib. Initially, electricity was supplied from a power station on the site, having five 600 kW Diesel-engine-driven alternators, but early in 1952, the power station was shut down and the excavator was supplied from the Board's system, a specially designed frequency-booster set being used to convert from 50 to 60 c/s. The installation was a great success and resulted in the purchase of similar excavator booster sets, and there are now two installations in this area at work on a new site near Bedlington, and two larger excavators being installed at Widdrington.

These large excavators are operated continuously throughout the 24 hours, except, of course, for maintenance, and the load on the supply system has, therefore, a high load factor.

Iron and Steel Works

The connection, if one may use that term, between the iron and steel industry and the electricity supply industry in this area goes back a very long way. In 1908, Mr. Charles Merz read a paper to the Iron and Steel Institute at Middlesbrough, in which he referred to the establishment of waste-heat power stations connected to the power company's system, which provided a ready outlet for the surplus supply not required by the works themselves. At present, the generating plants in steel works throughout the Board's area, with one exception, operate in parallel with the Board's system, consumers' surplus requirements being obtained from the Board and the surplus energy generated by the steel company being purchased by the Board. This combination leads to an efficient and mutually advantageous arrangement.

Other Heavy Industries

Increased productivity, which can most easily be achieved by providing more horse-power per man employed, is reflected in the substantial increases which take place each year in the sales to existing consumers as well as by the very much larger initial power requirements for new works. One large firm on Tyneside has doubled its power requirements in seven years, and it is a certainty that whenever a factory or workshop is re-equipped, the new tools will provide a greater output and will therefore require much more power than the old ones. One cannot help feeling that, as larger, more powerful and more expensive machine

ools are provided, more use will have to be made of shift work-g, with a corresponding improvement in the load factor.

Light Industry

The main industrial areas in the north-east—Tyneside, Wear-de and Tees-side—are all centres of basic heavy industry, and ere all badly hit by the industrial depression in the 1930's. It difficult for us to-day, in this time of full employment, to member just what this area was like in 1932, when one in three all insured workers was unemployed. Many attempts were ade to attract new light industries to the area, and in 1936 the overnment agreed to advance money for the construction of e Team Valley Trading Estate, which was the first trading tate to be started in this area.

There are now 34 trading estates in the area, and over 300 nants, employing 49 000 men and women, occupy factories on ese estates. The existence of these new light industries helps provide a better industrial balance in the area and provides a urther outlet for the use of electricity. Of course, not all the ght industries are situated on trading estates, and others have en attracted by the availability of female labour; examples of ese are a large woollen factory in the Tees area, which is con-ected direct to the 132 kV Grid, and a tobacco factory on yneside.

Traction

Traction is the only section of industrial supplies where the les, instead of going up, are going down, as trams and trolley buses are being gradually withdrawn from service and replaced by Diesel-driven buses. The supply to tramway systems was one of the best loads in the early days, and represented a substantial proportion of the electricity sold in urban areas. In this area, the North Eastern Railway was a pioneer in railway electrification, and supplies were first provided in 1904 for the electrification of the line between Newcastle and the coast, and in 1938, the electrification of the line from Newcastle to South Shields was completed. To-day, sales to the railways and light traction represent less than 2% of the total sales.

Commercial and Domestic Supplies

In the Introduction, I stated that development of the commercial and domestic load first received really serious consideration after 1923, and between then and 1939 there were extensive sales and development campaigns to encourage greater use of electricity by the commercial and domestic consumers. During the war, restrictions were in force which prevented much further development, and after the war the shortage of generating plant prevented a full resumption of these campaigns. Purchase taxes on electric fires, water heaters and other appliances were all designed to discourage the installation of new apparatus. In spite of all this, the load has gone on developing, and what is more, the load factor of this type of supply has improved, showing the wide diversity which exists in the use of the smaller appliances.

[Mr. Kenyon then illustrated, by means of lantern slides, the load curves and load factors of the various types of supply.]

Abstract No. 1978
Jan. 1956

NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By G. V. SADLER, Member.

"ETHICAL ASPECTS OF THE ELECTRICAL ENGINEERING PROFESSION"

(ABSTRACT *of Address delivered at* MANCHESTER, 4*th October* 1955.)

Although traditionally the Address from the Chair is based n the work on which the Chairman is principally engaged, he also allowed to say what he likes. I propose, therefore, to xercise this latter prerogative, and depart from tradition.

An address on the specialized nature of my own work would e, I consider, of more interest to an individual Section or Group, hereas, gathered in this room are representatives of all branches f the electrical industry in the north-west. We are all here as embers of The Institution whose sole reason for existence is, as s motto aptly puts it, to learn and to teach. By virtue of our embership, we ought also to be better electrical engineers, not ecessarily in the technical sense, but as men amongst men, and embers of an engineering community.

Membership of The Institution brings its duties and responsi-ilities, as well as its privileges. Our duties are known well nough. Whether we carry them out or not is a matter for ndividual conscience.

Our responsibilities are less well understood. We, as engineers hose tasks involve us in a multiplicity of details, administrative nd technical, have little time to sit back and consider the impact f technological development on other people, on other less eveloped nations, and even on the present conflict of ideologies n the world. Every new problem, once it is solved, produces nother one, and yet we cannot assume that there must be a echnical solution to every problem. The human element must come into it somewhere. The creation of wealth by continuous human endeavour is laudable enough in itself, but performed at the expense of human freedom and liberty, it is a travesty of human nature.

We cheerfully, it seems, sacrifice our liberty in the cause of technological progress. But where is it leading us, and how can we measure it? It is vital for engineers to measure the progress of their work by some known standard and take notice of these measurements, or eventually it will engulf them by creating problems impossible of solution by their own technology.

We can, of course, measure our progress in terms of output of available power per head of world population, or any other material form of measurement you desire, but that is not a measure of the progress of civilization, which, after all, is the only kind of progress which counts. As we all know, the real progress of civilization is not just a matter of mind and body; it is also concerned with things of the spirit as well. When we delve into the history and development of scientific thought, and its handmaid engineering practice, we find that the sciences have been closely related to culture and religion throughout the ages. To enable us to see the picture in this country, as it presents itself to-day, I propose briefly to highlight some of the events which have gone into its making, and in so doing, I must acknowledge having drawn on several sources of information which are listed below. It is sometimes assumed that modern science and engineering commenced during the 17th century, and that a good deal of

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loose and disconnected thinking previous to that time suddenly became rational and ordered. In point of fact, science has roots and ordered progress going far back into the years we now call B.C.

It is a widespread lack of appreciation of this fact which tends to regard scientific development as some isolated phenomenon, and causes it to appear to be so widely separated from other human achievements. All scientific thought does, of course, spring from early ideas and thoughts about nature and the natural progress of the world in which we live, and the Greeks, with their philosophies, exerted a very strong influence on human thought for centuries.

For centuries, scientific advancement was fostered by the Church, but from the 17th century onwards, science pursued its own course, although man's spiritual progress appeared at one time to be linked to scientific progress, through a common belief in the inseparability of both. In fact, the very course taken by science itself destroyed the age-long conception that science was a religious duty, and a part of the worship of God.

We should, however, try to see the background clearly before studying the present position as it affects the electrical engineer. His is the newest established profession, and it is also the one which enters into normal day-to-day life most actively. There is no implied slight here on the civil, mechanical or chemical engineer. The activeness of electricity is apparent to many a man and woman from the moment the electric alarm clock wakens them from slumber and they switch on the light over the bed, through a day of transport, telephones, radiators, television and the rest, until they are lulled to sleep again by the comfort of an electric blanket.

I spoke earlier of the need for measuring and equating electrical-engineering progress with that of civilization as a whole. What, then, is meant by human progress in the widest sense? We must recognize the human problem in the progress of technology. The western world is basically a Christian community, although I would freely admit that many deny this, or choose to ignore it. But I am speaking to responsible engineers amongst whom I feel sure the percentage of atheism is negligible, and of agnosticism quite small. At the same time, I am fully conscious of the wide variety of our membership, in which race, creed or colour is no bar to being united in a common technical interest which, I submit, must include the progress of humanity. If it does not, the purpose of electrical engineering is lost. Surely, in brief, human progress comprises a gradual refining of human nature over the centuries, a gradual elimination of the bad, and a more positive application of what is good.

So many people to-day regard higher standards of living as a natural right, as though the possession of a plethora of electrical and mechanical aids to comfort and pleasure would automatically engender wisdom, generosity and feelings of goodwill to one's neighbour. I am convinced that we have reached a point in history where those engaged in electrical engineering must take stock of what they are doing in relation to the general good of humanity.

In defining our responsibilities, I do not wish to over-emphasize the religious aspect, although, when we turn to history again, we find that religious influence has been most marked amongst the people of a nation at times of real moral and material progress. It exerts a stabilizing, as well as an inspiring influence, and yet, to me, it does not seem sound to find that technology has gone so far, and so fast, in the last 100 years, that the gulf between it and religion is growing exceptionally wide, and almost a cult of engineering worship is being established, many fearing or hoping that the engineer alone will determine the course of the future world. Engineers may well be asked by laymen, "Are the atoms and electrons you deal in real things?" We can reply in the words of a modern physicist: "Yes, they are in terms of patterns of events in the physical world."

People have become so accustomed to thinking of existence in terms of material things they can see, like books or chairs or stones, that it is difficult to visualize other forms of existence. The age-old question "Does God exist?" is primarily one for the theologians to study and interpret. But when we see existence, not only in terms of chairs or stones, and men and women, and remember other forms of existence, such as those atoms and electrons have, I do not think we can reject the idea of still more forms of existence possessed by spiritual beings. These are difficult questions, but they are contingent with the progress of mankind, and we must help to find the answers.

What can we do about it now? We can argue that the future welfare of mankind does not depend to any special degree on the morals of scientists and engineers. It rests on the morals of mankind as a whole, and that is a matter for ethics, and not for scientists and engineers. Perhaps, but we have our work to do, and obviously we cannot suddenly turn into teachers. As an example of what has been done—perhaps unconsciously—towards furthering the progress of man in recent times, witness the growth of radio and television, in which electrical engineering has played such a prominent part. We must not forget that both radio and television have indeed, in this and other countries, been the means of bringing many of the best features of art and learning before people in this generation, whose forbears were denied such great opportunities; and as such it has promoted progress.

I think that, as members of The Institution, we should give thought to means of bridging the gulf between technology and man's humanities, thereby increasing his hopes and reducing his despair. Individually perhaps, there is not a great deal that an engineer can do on his own. Those who design and administer can do much, as I know many are doing, towards husbanding the material resources of the world, which are being so ruthlessly expended in many ways for gain or profit. When they begin to run out, mankind as a whole may come to resent the manufacture of products designed only to last a few years; therefore they may be replaced, and thereby maintain employment. Mankind may resent the profligate use of materials in spare parts to bolster imperfect designs. The right use of the world's materials, which are not inexhaustible, is incumbent on us as trustees for future generations, and obligatory for the future well-being and advancement of under-developed countries, in which modern technology is being established for the sake of their raw materials, yet untapped.

Disce: Doce, the motto of The Institution, is to learn and to teach. I do feel that by acting together on this basis we can further the overall progress of mankind, and set an example to others. The potential of electrical engineering for world good is so high, if only we can ensure that the good news of its benefits is spread abroad, in order to allay misconceptions in the minds of millions of laymen. Their moral progress can be enormously advanced through the impact of material progress, if they are shown how to bridge the gulf between the two.

It would be more than a tragedy if the opprobrium of "smart Alec" ever came to be applied justly to any engineering community or institution, owing to any failure on their part to recognize their cogent responsibilities to those they lead. Looking ahead, are we wise to assume that The Institution of Electrical Engineers is imperishable, or the Institutions of Civil and Mechanical Engineers? The frontiers of engineering have broadened so immeasurably in the last 50 years, and the divisions have so melted into each other, that we must conceive of an Institution of Engineers presently emerging, combining all that

is best in the multiplicity of present Institutions. Of specialized sections, there must be plenty covering the everyday needs and activity which is the special work of each of us. Overriding and co-ordinating all this work would be a council of engineers—we might call them engineer philosophers—at whose meetings would be read no specialist papers, but ones in which breadth of vision and knowledge would integrate the myriad engineering developments into their right context, in relation to the needs of man and his progress in the world.

This, then, is the position we have reached to-day. I spoke earlier of the need for measuring the progress of our work, but progress in engineering does not consist in the mere passing of milestones ever faster and faster. If it did, the rest of the world would eventually be left behind, deprived of the incentive to better living which electrical engineers in particular can provide. Real progress must take the rest of the world along as well, to be leavened and encouraged by the technology which, directed aright, can go so far in helping to solve world problems of body and spirit.

It is my privilege to serve you as Chairman for the next twelve months, and if, together, we can kindle a better understanding of our professional interests amongst those who are unsure of them, and place science and engineering in its proper perspective in human affairs and progress, we shall have achieved much. How it can be done is a matter for thought and discussion, but I am convinced we ought to try. It is one way of fulfilling our obligations, and in so doing will, I think, help to draw into our ranks more of the right type of young men for which there is such vital need in the coming years.

Acknowledgments

The author wishes to acknowledge having drawn historical material from the following publications:

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Abstract No. 1979
Feb. 1956

NORTHERN IRELAND CENTRE: CHAIRMAN'S ADDRESS

By E. N. CUNLIFFE, B.Sc.Tech., A.M.I.Mech.E., Member.

"PROBLEMS AND PROGRESS IN ELECTRICITY DISTRIBUTION"

(ABSTRACT *of Address delivered at* BELFAST, 11*th October*, 1955.)

The distribution of electricity is like the distribution of any other commodity where the fundamental requirements are simply the delivery of the right quantity of material to the right place at the right time with the minimum amount of wastage. In our case the material is electricity, and the consequences of not complying with this basic rule involve a whole series of troubles ranging from complaints of poor regulation to widespread interruptions of supplies. The problems encountered in electricity distribution can be divided into two categories: those arising during the design and planning stage, and those associated with construction, operation and maintenance.

Dealing first with design and planning, the chief problem is that presented by the ever-growing demand for electricity and the need to determine with as much accuracy as possible the future incidence of this demand not only on the time scale but also geographically. An examination of the load-development chart for the Belfast area reveals an average rate of increase in demand of between 7 and 8% per annum for the past several decades, which corresponds very closely with the prevailing world-wide rate of increase. Practically the only setbacks which have occurred are those due to the two world wars and the economic depression in the early 1930's. The two salient points which cannot be overlooked are first that there is not the slightest sign of any slackening in this steady rate of increase, and secondly that in any period of 10 years the demand can be seen to have at least doubled, and consequently in any period of 20 years quadrupled. This is an important and remarkable fact which will be seen to have left its mark on the pattern of planning in the period under review.

Of equal importance to forecasting the whereabouts on the time scale of future demands for electricity is the problem of determining their probable geographical location. For when extending the distribution system to cater for random demands, a knowledge of the probable direction of future development can often justify the burying of more copper, the use of a higher transmission voltage or generally laying the foundation of a more elaborate system in the first instance than could otherwise be justified. For example, a study of the areas around Belfast in which have been sited the majority of the new housing estates planned since the war shows that development has tended to take place in three main directions, and has been guided there by suitable terrain and the attraction of existing main lines of communication. Consequently, when planning distribution schemes for these areas, it is sound policy to make somewhat more than the usual provision for future expansion.

The problems encountered to-day in planning are not always new. In fact, a brief glimpse into the history of the Belfast supply system will reveal a 60-year story of continual struggle to keep abreast of the ever-growing load, in which perhaps the most fascinating feature has been the way in which history has at intervals tended to repeat itself. Development over such a long period has not by any means consisted of the smooth expansion year by year of some basic system of distribution. Rather it was a progression by definite stages, the end of each stage being marked by the point when the existing system had been expanded to the limit of adequacy and it became imperative to carry out a major scheme of reinforcement using a more advanced technique. Such schemes have usually consisted of the superimposition on the existing system of a new primary transmission network having a higher voltage. We observe that these major changes in technique have tended to occur at roughly 20-year intervals, and if we also remember that the load-development chart revealed a fourfold increase in demand every 20 years, it is evident that the ultimate capacity of any of the major reinforcement schemes must be about four times that existing at

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present; in other words, allowing for similar amounts of copper being buried, the new transmission voltage should be about four times that of the old. Noting that the major steps in transmission voltage, namely 6·6 kV, 33 kV and now 110 kV, have followed quite closely this empirical formula, it is tempting to suggest the employment of this rule in forecasting the probable next step in transmission voltage around 1975; and if the figure so obtained appears a trifle unrealistic we must remember that our predecessors 20 and 40 years ago respectively would have regarded our present voltages in a similar manner.

One of the most troublesome aspects of planning is the necessity to limit the short-circuit energy to a value which can be dealt with by the majority of the existing switchgear on the system. This is particularly so in the compact Belfast area where the main feeder lengths are so short, and its influence upon recent planning can be observed in two main consequential features: first, a change which is taking place from the closely interconnected network of the 1930's and 1940's to the radially connected type of system, and secondly, the need to install reactors in all 33 kV feeders outgoing from the power stations.

Other features designed to control the upward trend of fault energy may be discerned from a study of a typical section of the Belfast distribution system. We can start with the assumption that the available energy on the 6·6 kV network fed from the step-down substations must be kept below 150 MVA, because it is not generally economical to standardize on larger switchgear in the ordinary distribution substations. This at once places limitations on the plant in step-down substations where it has been found expedient to standardize on 12·5 MVA transformers having reactance of 10%, each supplying a separate section of the 6·6 kV busbars and not being in parallel. It would, of course, be very desirable from the viewpoint of continuity of supply to operate the transformers in parallel, but this cannot be allowed unless either the size of transformer is reduced or its reactance increased, or alternatively the capacity of the distribution switchgear is increased to 250 MVA. Thus, in order to allow for the possibility of paralleling the transformers at a later date, all 6·6 kV switchgear at step-down substations is standardized at 250 MVA, whilst the 150 MVA switchgear now being installed on the associated distribution network is capable of easy conversion to 250 MVA.

The latest step-down substations are designed for three transformers, the third being connected as a standby to the other two so that the firm capacity of the substation can be regarded as 28 MVA, which it should be noted is just about the practical limit having regard to the difficulty of accommodating the many outgoing cables in the limited street space usually available.

Each transformer is supplied by a 33 kV HSL type of underground cable from the nearest main switching station where it has been found that the smallest practicable capacity of switchgear is 750 MVA. To install a smaller size would severely restrict the method of operation of the incoming main feeders from the power station in that not more than, say, two could be run in parallel. This would reduce the permissible loading on a feeder group and force a most uneconomical usage of the available copper. It should be possible to run at least three, and preferably four, feeders in parallel. This is one of the chief factors influencing the selection of 750 MVA switchgear for the distribution system.

Of equal importance to planning and design is the more practical side of the business, namely the construction, operation and maintenance of the distribution system, for in this field the consequences of any failure to recognize and solve the many problems are at least as serious, and moreover they can occur more quickly. Probably the best way of appreciating the variety and relative importance of such problems is to study the circumstances which cause supply failures. The main ideal of supply engineering has always been to maintain absolute continuity of supply, and any interruption must therefore be regarded as the result of some defect, if not of equipment, then of workmanship or indeed engineering administration.

With this end in view, a detailed analysis has been made of all important faults occurring during the past few years on the Belfast distribution system, excluding the low-voltage network but including plant in traction substations. From this it has been observed that the incidence month by month of these faults is purely random, no seasonal or annual relationship being noticeable. Furthermore, the moving annual totals show such a wide fluctuation that it has been difficult to discern, in the period under review, any conclusive trend either upwards or downwards in the general fault incidence. It does, however, appear that faults tend to occur in groups or batches, which supports the view that one really heavy fault can produce voltage surges which may weaken still further points of potential failure on the system and so produce for a period a heavier crop of faults than would otherwise have occurred.

The same number of faults has also been analysed on a different basis to show, first, the extent to which the various classes of equipment were involved and secondly the several causes of the faults. The main feature of the first investigation is that switchgear (which includes control and protective gear as well as fusegear) is involved in by far the greatest share of the troubles, i.e. 62%, which is not perhaps so surprising when we consider that there are more switchgear and fusegear units on the system than any other class of equipment. Cables and overhead lines are also responsible for a heavy percentage, i.e. 32%, which again is not unexpected considering the vulnerability of the long lengths of cables installed. In pleasing contrast, transformers and other converting plant are comparatively trouble-free, contributing to a mere 6% of the faults. In the second investigation the faults were analysed into their several causes, and it may come as rather a shock that the largest single group, i.e. 24%, can be attributed, not to electrical deterioration, but to mechanical deterioration of some form or another, which only proves how important it is for every supply engineer to have some mechanical training or experience. It is even more

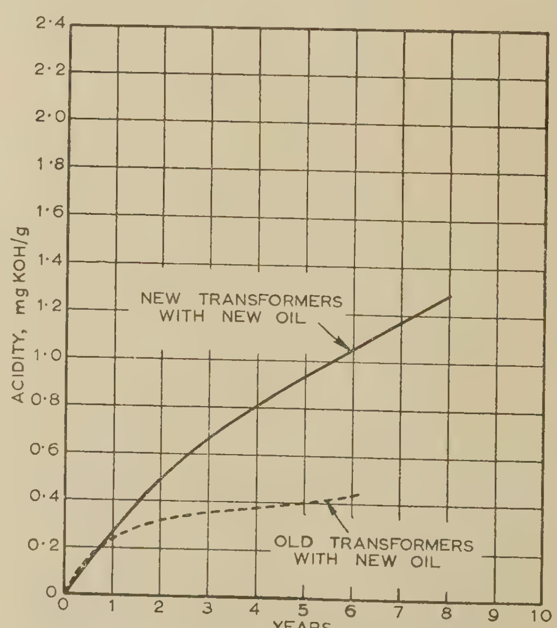

Fig. 1.—Average rise of oil acidity with time.

disconcerting to observe that faulty design, workmanship and mistakes between them accounted for no less than 27% of the troubles.

Following such an analysis of faults the next stage is a more detailed examination of the troubles affecting the main classes of equipment involved, and here we must start with switchgear, including fusegear. In earlier days the troubles encountered were serious and far-reaching, and although these have been overcome in modern designs, there remains a spate of lesser defects which, although trivial, commonly result in supply failures. Fuses and mechanisms have been the least reliable components, and the greatest single factor is mechanical deterioration, which may include such diverse defects as bent contacts, faulty operating mechanisms, sticking time switches, seized bearings or overstrained fuse elements. Faulty workmanship and design, also a main feature, embraces such troubles as interlocks which are not mistake-proof and badly-designed relays.

Transformers as a class have proved commendably reliable, although the anxiety caused by the transformer-oil acidity problem, which arose some ten years ago, will not easily be forgotten. This was tackled by washing down the core and windings, changing the oil from Class A to Class B, painting the insides of tank lids with anti-corrosive paint, adding above-oil ventilation, improving substation ventilation and accelerating the programme for the relief of overloaded transformers. By this means it has at last been possible to reduce what at one time appeared an alarming situation to one of manageable proportions. It was originally thought that replacement of the acid oil by new oil could at the best be only a temporary remedy, because the acid sludge which it was impracticable to clear away entirely from every nook and cranny would surely contaminate the new oil and hasten the formation of new acid. Fig. 1 shows rather surprisingly that in our experience the converse is the case.

The remaining essential ingredient of a distribution system is the underground cable which, after the switchgear, has been responsible for the next largest burden of troubles. It must, however, be admitted that these, although numerous, have not in the main been so serious as those due to switchgear. As an example, we need look no further than the first two 6·6 kV cables installed in Belfast which after 50 years of reliable service show no signs of undue deterioration and could easily last as long again. And finally, as an illustration of what the cable manufacturers have achieved in the art of underground super-high-voltage transmission, we can see the new 110 kV 3-core oil-filled cables which have just been commissioned in Belfast and are the first of their kind to be installed in the United Kingdom.

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Feb. 1956

SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By H. S. DAVIDSON, T.D., Member.

"DEVELOPMENTS OF THE HIGH-VOLTAGE TRANSMISSION SYSTEM OF THE CENTRAL ELECTRICITY AUTHORITY"

(ABSTRACT *of Address delivered at* BIRMINGHAM *3rd October*, 1955.)

The greater part of the Central Electricity Authority's transmission system is operated at 132 kV with a 275 kV system now being superimposed upon it, and in this Address the developments that have taken place during the last seven years are reviewed. In order to keep pace with the increases in generating plant and the growing demands of the Area Boards, the transmission system has had to be extensively reinforced and extended, and in the seven years under review, schemes estimated to cost £130 million have been approved for this purpose. The work involved has included the provision of new transmission lines and substations, the alteration and extension of existing lines and substations, and the modernization of old plant. It has resulted in an increase in the route mileage of 132 kV transmission lines from 3 700 to over 5 700 miles, i.e. an increase of 35%, and the total transformer capacity has increased from 14 300 to 23 400 MVA, i.e. an increase of over 60%. Of these developments, the most outstanding has been the decision to establish a 275 kV system involving the erection of some 22 substations and of 1 150 miles of overhead lines, of which 340 miles have been erected and 40 miles are now operating at that voltage.

In general, extensions of the transmission system fall into two categories: first, those necessary to deal with the export or import of energy at the generating stations and to interconnect them, and secondly, those needed to provide increased supplies to the Area Boards where such supplies are required on their systems. The transmission system must be designed so that the Authority's generating stations can be operated to the best advantage, as restrictions on the use of the most efficient generating plant, causing the running of less efficient plant, result in severe financial loss. The demands of the Area Boards must also be met, and to ensure this, long-term planning is necessary, load estimates for periods of eight years ahead being used for this purpose. Before decisions are made to establish new Grid points, all alternatives are considered and the best overall schemes are adopted. This was not always the case under independent operation, and already savings to the industry estimated at over £11½ million have resulted from this policy.

The developments during the period under review can conveniently be divided into sub-headings dealing with civil works, switchgear, transformers, overhead lines, cables and maintenance, to each of which reference is made.

Civil Works

The civil-engineering work includes the preparation of sites, and the construction of roads, foundations, structures and buildings. An example of the weights to be handled is that of a 275/132 kV 120 MVA transformer, which, when prepared for transport, weighs 105 tons, and has a total weight when installed of 210 tons. The areas of the sites have also increased with the adoption of higher voltages, and a 275 kV substation controlling 20 circuits is approximately 1 100 ft long and 450 ft wide.

A large measure of standardization of the civil-engineering works has been achieved, and although there are variations in the type and make of switchgear and transformers, the general layout of substations can be the same in many cases. This has resulted in the adoption of standard types of ferroconcrete structures which need only minor modifications to suit the variations to which I have referred. Ferroconcrete has almost entirely superseded lattice steel for structures, its main advantage being the

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elimination of painting, which, in the case of steel structures in live substations, is a difficult and expensive matter. In a few cases, special circumstances necessitate the use of indoor substations with consequent variation in the nature of the civil works.

Switchgear

The rapid expansion of the transmission system has meant an increase in the magnitude of the fault energy at many points, and much of the development under the general heading of switchgear has been related to this increase. The requirements are now for 2500 and 3500 MVA circuit-breakers at 132 kV, while at 275 kV the specified rating is 7500 MVA. In general, the busbars, isolators and fittings on the original Grid scheme were liberally designed, and little alteration to these has been needed, but many circuit-breakers in the older substations have had to be uprated. Circuit-breakers in use are bulk oil, air blast and to a limited extent small oil volume.

Restrictions on capital expenditure in recent years have been responsible for many of the innovations in the circuit arrangements at substations. The three-switch substation, which controlled two feeders and two transformers, has now been developed into the four-switch substation, which controls four feeders and four transformers. The layout is in the form of a square with a circuit-breaker in each side, and to each corner a feeder and a transformer are connected. In some cases, single-switch substations are used, and in other cases feeders have 132 kV circuit-breakers at the starting points only and are directly connected to transformers at the remote ends. In the larger substations, double busbars with section and bus coupler switches are used, and a recent development of the busbar arrangement has been to have the reserve busbar in the form of a letter U with the main busbar inside it. This arrangement allows connections to be made to the back or front of a substation with equal facility, and without resorting to high fly-over connections; it also reduces the overall length of the substation.

Generator circuits are normally switched at the transmission voltage and connected through generator transformers, synchronization being done across the 132 kV or 275 kV circuit-breakers. The reduction in the number of circuit-breakers used has inevitably complicated the protective circuits, the intertripping of several circuit-breakers often at widely separated points frequently being necessary on the occurrence of a fault. Busbar protection is commonly installed in the larger substations, and many of the older ones have been modernized by the addition of this protection.

Transformers

The capacity of transformers installed has risen, as previously stated, during the period under review from 14300 to 23500 MVA, and there has been a trend towards larger units, although the sizes range between 15 and 120 MVA. At bulk supply points, sufficient transformer capacity is provided to meet the load assuming the largest unit to be out of commission, and thus a minimum of two transformers is required at any point. Due regard is paid to the capacity of interconnections on the Area Boards' systems in assessing the firm capacity when more than one bulk supply point is concerned—yet another example of how co-operation between the Central Authority and the Boards ensures that the best use is made of all assets. In determining the capacity of transformers required, the overload capacity on cyclic loading, generally accepted as being 30%, is taken into account.

With more generators switched at the higher voltages, there has been an increase in the number of generator transformers. These transformers equal the capacity of the generators, and as in future the transmission voltage will quite frequently be 275 kV, banks of transformers of the order of 200 MVA stepping up from, say, 20 to 275 kV will be commonplace. For the interconnections between the 275 and 132 kV transmission systems, auto-transformers are being used, and normally these will be arranged in banks of 120 MVA units. Such transformers are now being installed as 3-phase units, and the only limitation to larger units would appear to be transportation. Decisions to fix fault levels at 250 MVA for 11 kV systems and 750 MVA for 33 kV systems have resulted in the transformer impedance being increased from 10% to $12\frac{1}{2}$%, and tapping ranges have also been extended to give improved voltage control.

Overhead Lines

Lattice steel towers are in general use, but limited use has been made of wood poles. The shorter spans necessary and the limitation to one circuit only at 132 kV would appear to confine the use of wood poles to a few special circumstances. Single-circuit steel tower lines are no longer erected, double-circuit towers being used throughout, even if only one circuit is required in the initial stages of development. The use of high-tensile steel has permitted a lighter type of tower, and advantage has been taken of this in the case of the 275 kV towers, many of which are now designed for future use at 380 kV. The towers are galvanized, but in most parts of the country, painting ultimately becomes necessary.

For conductors, steel-cored aluminium is used almost exclusively, but a small number of lines, most of which were erected in war time, have cadmium copper conductors. Two standard sizes of conductor are used, namely $0\cdot175\,\text{in}^2$ and $0\cdot4\,\text{in}^2$, giving circuit ratings of 90 and 120 MVA respectively at 132 kV. On the 275 kV system, twin conductors of the same sizes are used giving ratings of 375 and 570 MVA, respectively. A double-circuit 275 kV line with twin $0\cdot4\,\text{in}^2$ conductor has therefore a nominal rating of 1140 MVA.

Satisfactory protection against strand breakages due to vibration in the conductors continues to be obtained by the use of Stockbridge dampers. The practice of providing duplicate earth wires within a mile of a substation has now been abandoned, and no ill-effects have resulted from this change, which has the merits of simplifying the construction of the upper portions of the towers and reducing the number of types of towers required. On the twin-conductor lines, spacers are used to prevent clashing of the conductors. The type now in use provides a spacing of 12 in and allows a limited longitudinal movement of the conductors to take place relative to each other; they are fitted approximately 200 ft apart. Greasing of conductors has been adopted for use in certain locations as a means of preventing corrosion.

For straight joints and dead-end clamps, the compression type is used almost exclusively. This consists of a steel sleeve which is compressed on to the steel core of the conductor and an aluminium sleeve which is placed overall and compressed on to the aluminium. The compressions are made by the use of small portable compressors fitted with dies of the appropriate sizes. Such joints and clamps are simple to make and have given satisfactory service.

For insulation, the cap-and-pin type of disc insulator is in general use, and a considerable measure of standardization allows the interchange of various types. Glass and porcelain are used almost equally, an advantage of the former type being that damaged units are easy to detect, as the glass disintegrates, leaving the cap and pin intact. On the other hand, a porcelain unit can sustain a limited amount of damage and continue to give satisfactory service.

The first section to operate at 275 kV was made live during 1954 and runs between Staythorpe in the East Midlands Division

and West Melton in the Yorkshire Division—a distance of 41 miles.

Cables

The mileage of high-voltage underground cables is small in comparison with that of overhead lines—only 682 miles compared with 6485 miles. The number of separate installations, however, is fairly high, and extensive experience of cables at all voltages up to and including 132 kV has been obtained. The 275 kV system will call for the use of underground cable in certain circumstances, and at Staythorpe in the East Midlands Division two types of gas pressure cable and two types of oil-filled cables are being tested under service conditions at that voltage. The results of these tests will assist in the design of the cables which will be required in the future.

For installations up to 33 kV, solid types of cables are generally used as most of the runs are short, but in some cases and at higher voltages, gas pressure cables and oil-filled cables are used. Much progress has been made in standardizing cables, joints and fittings.

Maintenance

The aims and objects of those responsible for maintenance are first to prevent breakdown of plant by planned inspections, and secondly, to repair and restore to service as quickly as possible plant which does break down. The transmission system is designed to permit outages for maintenance purposes and to provide for security of supply under foreseeable conditions, but nevertheless there are those occasions when, by some unfortunate combination of circumstances, failure of supply occurs. Such occasions are, however, extremely rare, the reliability of the transmission system being of a very high order.

The complexity of certain of the switching arrangements to which I have referred has undoubtedly complicated the work of maintenance and added to the risks of interruptions of supply. It is of interest to note that the number of system faults in 1954–55 was 382 compared with 723 in 1948–49, despite the increase in the size and complexity of the system and the loads carried. The C.E.A. Research Laboratory at Leatherhead has made important contributions to maintenance techniques by its investigations of the many problems that have arisen. An example of this is in connection with the corrosion of steel-cored aluminium conductors, for which a system of sample testing, which includes measurement of the resistance of the conductor and of tensile strength of individual strands, has been evolved. From these tests it is possible to determine the need for replacement of conductors before serious deterioration has taken place, thus allowing the work to be programmed in advance. The amount of replacement so far required has been small, averaging for the last five years 140 miles per annum. As many of the conductors replaced have been in service since the early 1930's it will be appreciated that conductor corrosion is not a serious matter. It is hoped that even longer life will be obtained by the greasing of conductors already mentioned.

The performance of insulators is closely watched, and some developments of new types, notably the oil-filled type, have assisted in maintaining satisfactory standards. A further interesting development is that, under conditions of severe pollution, coating the insulators with grease has resulted in improved performance. On the overhead lines, live line testing of porcelain insulators is carried out—an agreed quantity of each type being tested annually. The number of faulty units so far detected is insignificant, except in a small number of cases where certain types were found to be unsatisfactory and were withdrawn from service. Suspected units are removed from service and check-tested on a high-voltage testing transformer before being rejected if proved faulty. The glass insulators, of course, do not require such testing.

Painting of the tower steelwork is necessary in most districts and involves planning of line outages during the summer months. As there are over 30000 towers in service, the magnitude of this task will be apparent. Continual efforts are made to improve methods of preservation, but in recent years some 1500 towers have been painted annually. In an attempt to overcome the problem, experimental use is being made of an aluminium alloy for the upper portions of towers; such a tower has been erected on a line in Birmingham. In the original Grid scheme, some towers were constructed from steel having a small copper content which, it was claimed, would retard corrosion. No positive evidence of its efficacy has been obtained, but time may yet show that it has been beneficial.

Deterioration of bushings of the condenser type used in 132 kV switchgear has been observed after many years of service, and methods of detecting it have been sought. Power-factor tests at or near the working voltage are the obvious solution but are not practicable with the bushings *in situ*. Some success has, however, been achieved by testing at 30 kV and removing suspected bushings for tests at higher voltages.

Transformer maintenance is largely confined to the tap-changing gear and, in particular, to the diverter switches. The frequency of overhaul varies with different types and conditions of service, but it is of interest to note that the wider adoption of automatic voltage control has resulted in increased maintenance being required, since the automatic operation is quicker than the human operator in reacting to changes of system conditions. Any design improvements that can be effected in tap-changing gear, particularly of the diverter switches, will be of value in reducing transformer outages.

The underground cable system calls for little maintenance, but with the increasing mileage of gas pressure cables, methods of detecting gas leakage are becoming important, and experiments in the use of radio-active tracer gases for this purpose are being made.

Conclusion

There are many items which have been omitted from the Address such as protection, metering, communications and system operation, in all of which developments have taken place, keeping pace with the growth of the transmission system and about which more could be said.

A word, however, should be said regarding the co-operation of manufacturers and consulting engineers with the Authority and Area Boards, which has made many of the developments possible. By such joint efforts, the Authority's transmission system has developed and will continue to develop as an example of sound engineering second to none in the world.

Acknowledgment is made to the Central Electricity Authority for permission to give the Address.

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SOUTHERN CENTRE: CHAIRMAN'S ADDRESS

By L. H. FULLER, B.Sc.(Eng.), Member.

"SOME ASPECTS OF DISTRIBUTION SUBSTATION DESIGN"

(ABSTRACT *of Address delivered at* PORTSMOUTH, *5th October*, 1955.)

Substation design is a subject on which very little has been written although there is plenty of literature on transformers, switchgear and individual components, and it seems remarkable that there is rather a dearth of information about the union of all these components into an ordered whole.

Regulations

Regulations are of the greatest importance.

First, we are governed by the Electricity Regulations, the most important being Nos. 1, 14, 17, 21, 25 and 30, and the 1951 edition contains valuable up-to-date notes by Mr. Swann.

Secondly, we must observe the Electricity Supply Regulations of 1937, reprinted in 1949, the important regulations on substations being Nos. 9, 10, 14 and 16. However, here we meet a difficulty—Regulation No. 10 states that the distance from a live conductor to a place accessible to an unauthorized person shall be 14 ft on the supports of overhead lines or in other suitable positions (other than outdoor substations). What, then, must be the distance from a busbar in a 33 kV outdoor substation to the ground outside the surrounding fence? Common sense answers 14 ft.

The third document to consider is B.S. 162: 1938, which is at present under revision. It is particularly useful for 33 kV outdoor-substation design, and a mandatory interpretation does no harm.

In all these documents, one theme recurs—all dimensions are stated to be minima, and yet many designers interpret them also as maxima. This is a most deplorable outlook, for if designs can be based on slight excess of the figures, how much easier it is to compensate for the many inaccuracies which may and frequently do occur during construction!

Basic Requirements

Given that a knowledge of the appropriate regulations is a requirement, there are two other basic factors to bear in mind. These are the degree of continuity of supply and the safety to property and life. The last is the most important—we can rebuild a structure, we can repair a structure and we can create life, but we cannot recreate "once the silver cord has been loosed or the golden bowl has been broken."

Therefore if in any assessment of a regulation you may be in two minds, it is well to err on the generous side. This is where common sense should be applied and where the voice of experience should not be heard in vain.

Dangerous Designs

Having regard to the highly individualistic development of substation designs, it is hardly surprising that many dangerous substations have existed from time to time, quite apart from those which are dangerous by virtue of the inadequacy of the apparatus inside them.

One of the chief causes of dangerous substations in the past, however, has been the tendency to allow them to outgrow their capacity.

Precepts

The following precepts may be of advantage in considering designs:

(*a*) If the requirement is not "in the book" common sense should give the answer, and if experience is also available it should be consulted.

(*b*) Segregation of plant is of the greatest importance. Gear of different voltages should not be cheek by jowl, and if a switchboard is other than small the bus section should be segregated. This also applies to cables—separation of voltages, and separation of main input cables from the distributors.

(*c*) Doors should open outwards, and should *not* have raised thresholds. Push bars should be fitted inside the exit doors. Common sense and experience will dictate the number of doors.

(*d*) Pebble-filled oil sumps should not project in front of switchgear, the access must by regulation be clear and unobstructed, and an edge of concrete in such a position is a definite hazard.

(*e*) With indoor switchgear up to and including 33 kV, there is nowadays no need to go to the expense of having an overhead crane, or indeed providing an outside lifting beam or gantry.

(*f*) During the last decade or so, more thought has been given to ventilation of switchgear and transformer chambers, both having often been neglected in the past. As regards switch chambers, there was frequently no ventilation at all, which resulted in sweating and insulator flashover. Through ventilation is now provided, although there are two schools of thought, one using temperature as the criterion for switching on heaters, and the other humidity. Common sense dictates that the latter is the better, since dampness and not cold causes insulator failure. A good rule is to have the cold inlets set away from the switchgear to avoid cold air impinging directly thereon.

(*g*) As regards the civil engineering side, high ceilings are not necessary, although the height must be at least 7 ft. Roofs should preferably be of concrete, and nowadays precast concrete beams in great variety are available—a little care in design can result in a good appearance. As regards brickwork, for small buildings 9 in is adequate, and we can use 11 in cavity walls—again two schools of thought. The important thing to bear in mind, however, is the present very high cost of civil engineering works, and any reasonable way of reducing these is to be commended.

Choice of Site

In the past, many of us have received local requests for some harmonization of a substation with the surroundings, which could often be done; but we have also heard of requests for the camouflage or disguise of a substation as a house, and even in at least one case as a chapel. Luckily these ridiculous planning impositions now seem to be extinct. It seems to me that an undisguised substation can often be a pleasant relief from an interminable vista of villas all deadly like, and frequently, alike deadly.

We may now be in a more enlightened age as regards choice of site, and it appears to be now more generally realized that substations are laid down for the well-being of the community by providing or maintaining one of the greatest amenities possible—a supply of electricity, which outweighs so many of the other amenities.

Cable Entries

One of the most vexed questions for many years has been the method of bringing cables into a building. This may, in fact,

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sometimes be governed by the position of the switchgear cable boxes—a disadvantage of some forms of switchgear being the low level of the glands. The easy method is to use a cable trench, and in some cases a basement, but these methods suffer from two disadvantages—they are expensive, and they do not readily give segregation of cables.

There are two ideals—to get the cable out of the substation by as short a route as possible, and to keep it separate from other cables—and there are only two ways to satisfy these ideals. These are by the use of separate cable pipes or individual cable slots. Pipes can more easily be used when the cable box is a reasonable distance above floor level, and slots can be useful when the cables go straight out at the rear, but unfortunately there are many cases where cable trenches are necessary. Even then it is not difficult to segregate the main cables from the distribution cables.

Oil sealing methods are well known, and they are aided by lightly grouted trench covers and the fireproofing of all cables in air in the substation.

Small Distribution Substations

When demands for electricity for domestic purposes became general, it was realized that a cheap form of housing was necessary for the switchgear and comparatively small transformer; hence the steel kiosk, which was used in great numbers.

A successful attempt was made to overcome the disadvantages of the steel kiosk, and also to improve its appearance, by using precast concrete structures, which were erected by direct labour from prefabricated parts and were remarkably cheap.

The greatest non-productive cost of an ordinary distribution substation is that of the civil engineering works, and so the greatest practical advance made recently is the extension of the use of the completely outdoor 11 kV substation. This caters for a 500 kVA transformer with fuse protection, and many combinations are possible. Factors in favour of its extended use are the improved h.v. isolators and fuses now available, the universal use of outdoor transformers as standard, and the ready acceptance by local authorities of the design, bearing in mind that it is exempt from planning permission by virtue of its small cubic capacity.

66 kV and 33 kV Outdoor Substations

There are not so many 66 kV outdoor substations in popular use, but what applies to 33 kV substations, as regards outdoor installations, also applies to 66 kV, subject to a site-area-factor increase of about 30%.

In a small installation it is nearly always possible to arrange a direct overhead lead-in from the line to the switchgear, either by an offset arrangement or by a direct sloped dropper. In a large installation cable terminations can hardly be avoided, especially if the umbrella effect of a large number of immediately radiating lines is to be avoided.

Designs for 33 kV outdoor substations have been many, and a large number have been built on the basis that, when maintenance is required, large portions must be made dead. It thus behoves us all to interpret B.S. 162 with our native common sense, and design for sectionalization for maintenance purposes. If we can make some real saving by an appropriate design, it is worth while. In any normal in-line arrangement, for a given number of circuits, there must be the same number of busbar sections with their attendant isolator connections. A back-to-back arrangement, however, will halve the number of these busbar sections and economize in copper and space.

Reasonable Risks

"Reasonable risks" is a term we do not hear enough. Is a failure going to affect a few consumers or a few thousand? How much load will be shed? Will other installations be affected? Is the failure likely to grow into a calamity?

The answer is really the same—is it a reasonable risk? In answering this question, several important factors should not be forgotten, such as the increasing reliability of modern equipment, better overall maintenance, better installation techniques, the use of unearthed construction of overhead lines, increased interconnections and better design of substations. Finally, will the job stand it?

The realization of what is a reasonable risk has shown good results in the simplification of equipment, which has taken place concurrently with, and as a result of, standardization, the most spectacular perhaps being in distribution transformers. In considering duplication of feeders or equipment, a reasonable view would be to consider the worst fault and leave it at that.

The increased reliability of plant and the effect of the other factors just referred to are, in my view, powerful reasons for a simplification of protective systems and devices. This is one advantage of an overhead distribution system—it is easy to group-fuse several transformers, and damage is both easily discernable and easily repairable. Incidentally, this is a good illustration of a reasonable risk. Pole transformers are accessible electrically and are small, so they are group fused; ground transformers are generally much larger, and being supplied by cable, are not so accessible electrically, and are, in general, individually fused.

Another risk of increasing importance, and about which there are diverse opinions, is the vexed question of transformer noise. With the growing number of substations and the increasing difficulty in finding good sites, the noise problem can become of importance, but it is a risk which obviously must be taken. Naturally, transformers are not erected close to houses except in the last resort, and even then some consideration of layout may be of assistance.

The Future

The role of a prophet is profitless, but the following may be seen during the next decade:

(*a*) Universal use of cold-rolled steel in transformers, resulting in a higher distribution efficiency and some reduction in size.

(*b*) More extended use of silicone-insulated transformers as the result of greater difficulties in finding safe positions for transformers in buildings in the more congested areas.

(*c*) Greater use of 11 kV outdoor circuit-breakers for transformer and feeder control in suburban and rural areas. This is a greatly needed development.

(*d*) Increased use of solid or semi-solid connection of transformers without fuses or circuit-breakers.

(*e*) Much greater use of 33 kV as a distribution voltage in addition to its use as a transmission voltage.

(*f*) Simplification of 33 kV switchgear, and especially the reduction of the control equipment, with greatly simplified mounting arrangements.

(*g*) Reduction in the number of indicating instruments.

(*h*) At major 66 kV or 33 kV substations, increased use of the miniature type of control board using telephone-pattern relays and simplified cabling.

(*i*) As the result of improved operation and techniques, some swing of the pendulum away from the more elaborate safety precautions.

(*j*) Reduction in the number of 33 kV circuit-breakers, both indoor and outdoor—with the development of air or oil-break switches suitable for dealing with load currents and closing on to faults.

(*k*) Extended use of oil-break switches as integral parts of 11 kV metalclad switchboards.

(*l*) The adoption of transformer noise standards.

(*m*) Extended use of integral substations comprising 11 kV transformer with h.v. and l.v. fuse gear incorporated on the tank.

(*n*) Pole transformers of 200 kVA capacity becoming a commonplace instead of a comparative rarity.

(*o*) Great numbers of secondhand 4½ and 5 kVA pole transformers on the market or scrapped.

Reverting to the present, may I appeal to all young engineers to take a keen interest in the subject of substation design, which I regard as the most important aspect of the construction of electrical distribution systems.

I might perhaps leave this thought with you. If a fatality occurs and "He shall return no more to his house, neither shall his place know him any more," will you have to say that it was because of your faulty design or can you say that your design incorporated all reasonable precautions? Your conscience will give you the answer.

Paper No. 1982
Feb. 1956

WESTERN CENTRE: CHAIRMAN'S ADDRESS

By T. G. DASH, J.P., Member.

"THE MINING ELECTRICAL ENGINEER"

(ADDRESS *delivered at* CARDIFF, 13*th October*, 1955.)

The mining industry is not well represented in the activities of The Institution. This is due to the fact that, despite the extensive use of electrical power and the large number of electrical engineers employed in the industry, there are very few possessing the necessary qualifications for membership.

The mining industry in the past has not attracted the technically qualified electrical engineer for various reasons, examples of which are given below:

> The working conditions have not always been congenial. Coal mining, in all its aspects, has always been a "dirty clothes" job. Underground the engineer has had to work in conditions which have been dusty, and the restricted space in which machinery was placed made his work very difficult. On the surface, owing to the nature of the processes, dirt and dust were again encountered, so that all personnel were forced to go home in a dirty condition.
>
> The salaries paid have not compared with those of other industries. Generally speaking, prior to nationalization, the electrical craftsman and the engineer were not paid wages and salaries comparable with those of mining engineers or electrical engineers in other heavy industries.
>
> The status of the electrical engineer in the industry has not been as high as it is at present. Often the person to whom he was responsible did not fully appreciate his abilities or the economical advantages of electricity in mining operations.

This situation was to be deplored because at the present time the industry is badly in need of men having training and experience of the standard required by The Institution for corporate membership.

However, since the advent of nationalization, conditions have slowly but steadily been improving. Conditions of work underground have undergone a change in that the dusty conditions which used to prevail are being reduced by the introduction of water infusion and wet cutting of the coal. Attention is being given to the placing of machinery in more accessible positions where it can be better maintained. Another extremely important factor is the introduction of pithead baths, which has meant that all workers can leave their dirt and grime at the pit. This will soon be a feature of every mine in the country. The salaries now being paid to engineers have increased, the present rates being comparable with those in other industries.

The status of the engineer is improving. This is due in some part to the more enlightened view now held on the importance of electrical power in mining operations. Another factor, affecting in particular the engineer-in-charge of the mine, is the introduction of the Coal Mines (Mechanics and Electricians) General Regulations, 1954; these will be referred to later.

Mr. Dash is with the National Coal Board (South Western Division).

In the pre-war years, electrical engineering was developing its industrial applications throughout the country, but there was not a comparable growth in the mining industry, particularly with reference to work underground. This was because the use of electricity in and near the face was not encouraged owing to the dangerous conditions which could arise as a result of the presence of gas. In such conditions an electric spark could cause a very serious incident. There has, however, been slow but steady progress towards reducing this danger by improving the ventilation underground, thus ensuring that any accumulations of gas would be sufficiently diluted to render them harmless. The theme of the mining engineer has recently been to make the mines safe for the use of electricity as far as possible, and not wholly to depend on apparatus being perfect in its construction so that it could safely be used in dangerous atmospheres.

On the surface, electricity has been used to a degree comparable with many other industries. An indication of this is the number of large machines of 750–2000 h.p., both a.c. and d.c., which have been installed for winding engines and for driving air compressors.

With regard to the generation and transmission of electric power, the mining industry has pioneered a number of developments. For instance, in South Wales some years ago a mining company was the first in this country to utilize a 33 kV transmission system with the generating plant using steam at a pressure of 350 lb/in^2 and a temperature of 750° F. This company was also among the first to have boiler plant with steam at a pressure of 1500 lb/in^2 for driving turbo-generators. Such plant needed good engineers, but their numbers were few, and it is to their credit that, although some of them were not highly trained technically, they had a good fund of common sense to enable them to maintain the system in such a way that a reliable supply of electric power was available for the collieries at all times. Although some colliery companies were appreciative of the benefits of electric power, there were many who either did not have the capital to spend on electrical plant or, as was often the case, were not progressive enough to appreciate the advantages to be gained by its use.

This then was the general pre-war picture, but in the last decade, and especially since nationalization of the mines in 1947, there has been a remarkable advance in the use of electricity for all purposes in mining and particularly for coal winning and conveying underground. The graphs shown in Fig. 1 give some indication of this growth in the South Western Division in the last few years.

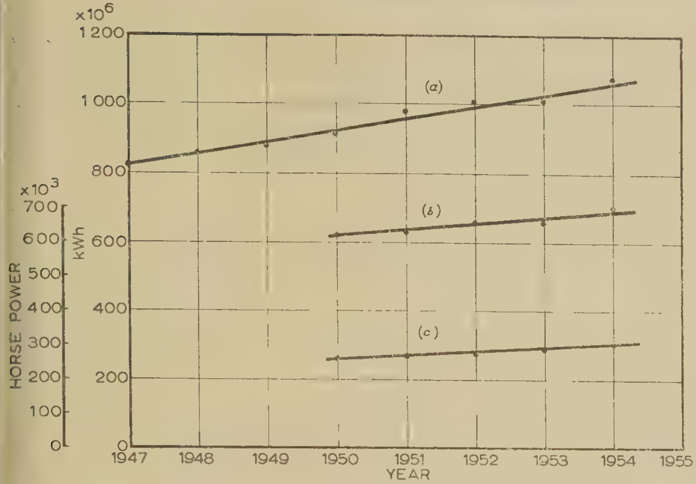

Fig. 1.—Growth of the use of electricity in the South Western Division.

(*a*) Number of kilowatt-hours consumed per annum.
(*b*) Total horse-power of electric motors (underground and surface).
(*c*) Total horse-power of electric motors (underground only).

To gain some idea of how great and rapid the change has been, it is well to remember that in a comparatively short time the basic method of mining coal in a number of mines has fundamentally changed. In some collieries there has been a change from a manual to a mechanized system, while in others, electricity has replaced compressed-air power. To further illustrate the changing conditions, the following statistics concerning the amount of machinery installed in collieries throughout the country are of interest:

	1938	1951	1954
Electric motors..	54 800	94 508	117 636
Coal cutters	7 700	11 522	11 919
Conveyors	7 800	23 262	28 151

These figures do not reflect fully the changes which have actually taken place, but they give a good guide to the trend.

The increase in the number of electrically-driven machines to remove coal from the faces and to convey it to the pit bottom, and thence to the surface for preparation for the market, has meant that a large amount of new equipment, much of it flameproof, has had to be introduced for the first time. There has therefore been a growing demand for well-qualified and well-trained electrical engineers in the industry to deal with the new situation. Even the attitude of mind of the existing electrical-engineering staff has had to be changed, because formerly nearly all their activities were confined to the colliery surface. Now they are increasingly concerned with all aspects of underground work.

The rapid development has made it necessary to train men to cope with the additional work. There is a shortage of all classes of electrical staff, from the craftsman necessary to maintain the standard of the trade with regard to the installation and maintenance of electrical apparatus to the chartered electrical engineers required for the development and application of electrical power on a sound engineering basis.

An extremely important factor in the changing situation has been the introduction of the Coal Mines (Mechanics and Electricians) General Regulations, 1954. In the memorandum on these Regulations, the Ministry of Fuel and Power states:

> The object of the Regulations is to secure the proper installation, examination, testing and maintenance of mechanical and electrical plant of which more and more is being installed in mines. The Royal Commission on Safety in Coal Mines which reported in 1938 emphasized the importance of this matter, and the growing use of electricity in mines and intensive mechanization in recent years has increased the need for new requirements.

Under these Regulations the electrical (and also mechanical) craftsmen at the mine hold statutory responsibilities. The memorandum further states:

> They have either to supervise or themselves to carry out:
> (*a*) The installation of all plant;
> (*b*) The examination and testing of all plant before it is put into use after it has been newly installed or reinstalled, or repaired;
> (*c*) Its maintenance in safe working condition in accordance with the Regulations; and
> (*d*) The systematic examination and testing of all plant. . . .

In order to carry out these duties, the Act indicates that the craftsmen must have a certain standard of technical and practical experience. The technical qualifications required of a colliery-unit engineer is at least the Higher National Certificate or its equivalent, whilst the craftsman will require an Ordinary National Certificate or its eqüivalent. The setting of this standard and the responsibilities which the Regulations enforce cannot but help to improve the status of the engineer.

The National Coal Board has developed a system for the progressive education of colliery employees, which is known as the *Ladder Plan*. This, together with the National Apprenticeship Scheme provides for boys being enrolled as apprentices for training as engineering craftsmen. They spend five years in the different engineering workshops and are allowed one day per week for technical education. At the end of their apprenticeship, provided that they make satisfactory progress in their practical and theoretical work, they can be certified as *electricians for the mine*, as required by the Coal Mines Regulations. The standard of technical training is equivalent to that required for the Ordinary National Certificate. The most successful trainees are given further opportunities to qualify as *electrical engineers in charge of the mine*, which can also lead to their obtaining the qualifications necessary for corporate membership of The Institution.

In addition, the Board has also brought into operation a scheme of directed practical training. Men for this scheme are enrolled from those possessing the qualities required for administrative or technical responsibility, and they should have degrees, diplomas or comparable qualifications in electrical engineering. Men employed in the industry who have reached the Higher National Certificate or a comparable standard and who show promise of being competent and fully qualified professional engineers are also eligible for enrolment. They are given three years' special training in work which will be useful in preparing them for positions of responsibility in the industry. As stated in the "Guide to the Scheme of Directed Practical Training" published by the National Coal Board, the following main opportunities are offered to electrical engineers:

> (*a*) Executive posts in charge of electrical installations at large collieries or in charge of power stations and central workshops.
> (*b*) Semi-executive posts at Area, Sub-Area and/or Group level, carrying technical responsibility for supervising, through the colliery manager, the work of colliery engineers, and shift electricians at collieries. These posts will normally carry the primary responsibility for development and reconstruction work at collieries, together with the responsibility for ordinary maintenance work. They call for both technical and administrative ability.
> (*c*) Posts of a more consultative character at Divisional and National level primarily concerned with planning, development and research, and with administrative questions arising from the development of engineering services.

This scheme, together with the Ladder Plan and the National Apprenticeship Scheme will ensure that, in time, engineers of all grades will be available to meet the increasing demand.

It is to be regretted that only a small percentage of mining electrical engineers are qualified to be members of The Institution.

The new Regulations of the C.M.A. and the growing use of electrical power over a wider field in mining will improve the quality and increase the number of mining electrical engineers, and many will, I hope, see the need of seeking election to The Institution. Besides the advantages which membership will afford them, I feel that The Institution will benefit from an influx of men from this industry. Their experience in the electrical world is rather unique and can surely be of interest to other sections of industry, thus assisting the aims of The Institution. With experienced men of high standing from all industries in which electricity plays an important part, the objects of The Institution can be best achieved.

Abstract No. 199
Jan. 195

EAST ANGLIAN SUB-CENTRE: CHAIRMAN'S ADDRESS

By E. T. NORRIS, Member.

"MAN AS AN ENGINEER"

(ABSTRACT *of Address delivered at* NORWICH, 12*th October*, 1955.)

It is the privilege of an Institution President or Chairman in his Inaugural Address to choose any subject he pleases and to discourse on it in his own way without control of referees or papers committees, and so at least to his own interest and satisfaction.

My choice this evening is a broad study of human effort in the development and progress of electrical engineering as we know it to-day.

I am doing this on the basis of an engineer talking to engineers —not as an appreciation or build-up of scientific and engineering achievement, but on the theme that we are all human beings with human limitations and weaknesses. Some of us have more ability than others, and a few merit the title of genius, but we are all groping more or less in the dark with far more failures than successes—constantly achieving a little progress and equally constantly slipping back a little, yet nevertheless steadily increasing all the time our understanding and control of the forces of nature.

Human effort is the essence of engineering progress, or indeed of any other progress. Its nature has changed in quality and form in the course of this progress. It is convenient at first to consider these changes chronologically; that is, in their natural sequence, and for this purpose they may be divided into three stages.

(i) *Individual and Isolated.*—In the early days of scientific development—200–300 years ago—scientific studies were carried out mostly by isolated individuals. The subjects studied were sensible; I do not mean intelligent or reasonable, but, more literally, studies of phenomena appealing to the senses. This meant that in general they were either tangible or visible phenomena and so spectacular that they fascinated or excited the curiosity of contemporary society. We must remember that there were no technical journals in general circulation. Information was interchanged by personal visits or correspondence or by conversations frequently at second or third hand.

The approach to these subjects of study was naturally analytical rather than synthetic. It was perhaps too crude and primitive for us to call it a scientific approach, but we may generously refer to these early workers as scientists.

(ii) *General but Unco-ordinated.*—Interest in scientific and engineering matters became more widespread and practical application became possible, initiating the industrial era and with it the electrical engineering industry. Machinery became commonplace and began its prime function of saving and assisting human labour. In consequence, local finance and commercial activity became concerned.

The latter part of this period saw the origin of personal firms such as Brush, Ferranti, Parsons—men who laid the foundations of electrical engineering. We may be proud that many of these names are still perpetuated in our industry.

(iii) *Organized and Directed.*—Commercial and industrial activity grew to such a scale that it became of national concern both technically and financially, leading in short to the engineering world as we know it to-day. This position is of course well known to all of us.

The growth of engineering beyond even ordinary commercial and industrial interest is now so great that it has evoked national control and direction. These are dictated by finance and even political and certainly national interests.

The various sciences contributing to engineering are now so interrelated and interdependent that there becomes need for directorial control. This trend towards large organizations and amalgamations necessitates, instead of the individual worker of early days, a pyramid of various strata. At the top there must be an administrator or body directing the policy of research and development, below that a stratum of administration and supervision, below that delegation to the actual execution of the work, and so on down to the machines that are actually going to do the work. This organization in direction is of course not only essential but beneficial in that it enables vast resources and capacity to be co-ordinated and utilized efficiently.

The complications and complexity of engineering development have thus greatly increased. It has become necessary to break down any major development scheme into teams of workers— each working under a leader and each team contributing its part to the main development. One could not, for example, conceive of a digital computer as a one-man development.

In the early stages, human effort was devoted to saving physical labour and replacing it by machinery. Now that this has been achieved, at least so far as most heavy manual work is concerned, human effort has turned more to saving mental labour and mental alertness. For example, digital computers save calculating labour, whilst automatic control and protection replaces mental alertness. An engineer in control of a power station or a telephone exchange does not now have to continually and periodically inspect every pump or every bearing lubrication or every contact. He can sit at a desk and have full information on the performance of every process and machine brought to him. For this purpose he does not even have to be awake; alarms will take care of that. Automatic control will ensure that all processes are carried out, and automatic supervisory control will not only intimate when anything is not working properly but to an increasing extent will automatically take steps to correct or replace the faulty component.

Mr. Norris is with Ferranti Ltd.

Abstract No. 1983
Feb. 1956

NORTH LANCASHIRE SUB-CENTRE: CHAIRMAN'S ADDRESS

By W. WARD, Associate Member.

"DEVELOPMENT AND PRODUCTION OF D.C. TRACTION EQUIPMENT"

(ABSTRACT *of Address delivered at* PRESTON, 12*th October*, 1955.)

Some 30 or 40 years ago the d.c. system of railway electrification was confirmed for this country, and manufacturers of electric-traction equipment in the United Kingdom also decided to concentrate on the design and manufacture of d.c. traction equipments, judging at the time that d.c. traction would win a predominating preference among the operators of railways throughout the world. The advent and rapid development of the mercury-arc power rectifier during the following two decades accelerated the development of 3 kV d.c. equipments to a standard of high reliability, and it could be said with some justification that 3 kV d.c. schemes, on balance, held some preference over low-frequency single-phase systems with their more costly sub-stations and relatively complicated motors. Evidence for the above facts is found in the rather wide adoption of 3 kV d.c. systems in South Africa, South America and the Continent of Europe.

More recently, progress in overhead a.c. electrification at standard frequency is once again challenging the d.c. position. Indications to date, however, could suggest that this latest development may not necessarily change appreciably the preference for d.c. as against a.c. traction motors.

At present, some 25 years later, mobile mercury-arc rectifiers are available in multi- or single-anode types to enable d.c. series motors to provide probably the most economic means of motive power under a 50 c/s single-phase overhead line. The d.c. series motor starts on full field strength, thereby developing maximum torque, and throughout the full range of tractive effort and speed the commutating conditions are inherently stable. By contrast the 50 c/s single-phase series motor is seriously limited by commutation difficulties at starting, which involves severe arcing and burning at the brushes due to the induced voltage in the coils being short-circuited by the brushes. Further, the commutating field must be adjusted at stages in the speed range by modification of the shunt-connected diverter resistance.

B.S. 173 indicates normal maximum and peak values of temperatures which apply to traction machines in continuous and abnormal duty, respectively. Such temperatures demand suitable insulation materials, since the useful electrical life of any machine is determined by the resistance of its insulation to ageing, which is a function of temperature and time. Developments over the past years have raised the level of performance of insulation systems, notably in respect of increased thermal endurance and improved space factor. One development giving higher slot-space utilization in the armature slots, combined with a reduction in the copper eddy-current losses, is the use of shallow conductors in a double or multi-layer arrangement.

Mechanical problems arise behind the commutator risers, where the double or multi-tier formation of conductors in the coil side must be aligned in a single-tier formation for connection to their respective commutator bars. The use of shallow conductors in these forms increases the problem of obtaining optimum adjustment of commutation compensation to meet the requirements of all coils in a given slot.

Increases in armature speed have been made possible largely as a result of corresponding improvements in commutators. The commutator as a mechanical structure must be completely stable under widely varying extremes of temperature and speed. By virtue of the multiplicity of its component parts, the combined assembly presents a mechanical problem of many intricacies. Conventional archbound and wedgebound types of assembly are used, with some preference for the wedgebound construction for machines subject to the highest duty.

Commutator segments are now usually made in silver-bearing copper to obviate the occurrence of low-temperature annealing during dip soldering operations. Less than $0{\cdot}1\%$ of silver increases the annealing temperature from approximately 200° C (depending on the degree of cold working) to between 300° C and 350° C, i.e. from below to above the temperature necessary for soft soldering.

Since the nominal maximum and peak temperatures of armatures in service may range from 145° C to 160° C the choice of a suitable solder for the commutator joints is important. Soft solders are still in general use, but the tendency is to avoid the tin-lead solders on account of low tensile strength between 150° C and the tin-lead solidus at 183° C, which leads to solder creep and throwing within this range. Proprietary high-melting-point soft solders are now available, such as tin-antimony and lead-silver alloys with solidus temperatures of 236° C and 294° C, respectively. Provided that the tin-antimony alloy is kept lead-free, it retains its strength well up to 200° C.

The armature soldering operation needs to be very rigidly controlled in that a satisfactory joint must be made in a minimum time of immersion in the solder. To achieve this, the storage bath of solder is kept at a high temperature (400° C) so that when the solder is flooded around the pre-heated commutator (100° C) the temperature of the commutator joints is quickly accelerated to approximately 40 or 50° C above the liquidus temperature of the alloy, when fusion of the joints is assured and the solder is then run back into the storage vat. Prolonged immersion in solder at these temperatures tends to soften hard-drawn copper bars, and therefore the temperature around the commutator periphery is continuously measured by pyrometer and the solder withdrawn when the minimum temperature indicated above is reached.

The total amount of unbalance in an armature is made up of the sum of a number of excesses and deficiencies in weight, which can be conveniently resolved into two forces operating at each end of the armature and constituting a mechanical couple. As the couple is propagated by centrifugal force it follows that it can only be located when the armature is running. All traction armatures are therefore dynamically balanced in high-production balancing machines, which provide facilities for adjusting the weight and angular position of artificial counter-balance weights mounted in the balancing head. The bottom cradle of the machine is supported on two sensitive fulcrum bearings, while the upper cradle may be racked to bring either balance plane into line with the fulcrum bearings.

Nowadays the necessity of a minimum of unsprung weight is seldom raised, and fully-flexible drives between motor and axles are no longer considered essential for high-speed service. The perfection of a well-known rubber bushing has in recent years offered a satisfactory solution to the problem of providing a limited but sufficient degree of deflection between gear rim and hub in the modern resilient gearwheel.

Mr. Ward is with the English Electric Co., Ltd.

Abstract No. 1984
Jan. 1956

NORTH SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. KNOX, M.Sc., Associate Member.

"ELECTRICAL INTERFERENCE"

(ABSTRACT *of Address delivered at* DUNDEE, 12*th October*, 1955.)

Owing to the exceptional expansion of electrical engineering, the profession is tending to become the sphere of specialists. The development of equipment and techniques may affect adversely aspects of electrical engineering other than those they were particularly designed to serve. It is inherent in this matter of electrical interference that, in general, those equipments using smaller powers and employing higher frequencies suffer most. I propose dealing only with three major aspects of the problem. My aim is to illustrate how trouble arises, to give some indication of the magnitude of the problems, the methods adopted to limit or overcome it, and the legal aspect where it has been necessary to have recourse to statute to control it.

Inductive Interference between Power and Telephone Lines

Inductive interference arises when e.h.v. power lines are built close to and running parallel to telephone lines for long distances. The precautions to be adopted are determined by the Postmaster General under powers conferred by Electricity Supply Acts. Where protection is necessary it usually takes the form of the power authority arranging to limit the earth-fault current that can arise on its system to a figure determined by the physical conditions existing. The aim is to limit the induced voltage in the telephone lines under power-fault conditions to 430 volts. In special cases a relaxation is sometimes permitted up to 650 volts.

Where limitation of the earth-fault current would cause an unreasonable restriction on the operation of the power line, the Post Office usually undertakes the protection.

This is achieved by:

(*a*) Installation of three-electrode gas-discharge tubes at intervals along the telephone lines. The effectiveness of this method depends on satisfactory earthing at each protection point. Achieving this is often difficult, as the main source of trouble usually occurs in narrow Highland valleys where the earth resistivity is high.

(*b*) Sectionalizing the telephone lines by isolating transformers, which is a simple and effective method, but entails the use of a.c. signalling on the telephone route and the provision of special terminal equipment to achieve this. The equipment designed for use in this country uses trains of 50 c/s impulses for dialling and other signals. So far, it has only been used on various routes in Scotland. In one case, in order to limit the number of telephone lines on which protection was necessary, several new telephone exchanges were opened. This shortened the subscribers' lines to such an extent that inductive trouble was avoided. The protection was then provided on the junctions to these exchanges.

Corrosion of Underground Plant

A high proportion of corrosion arises from electrolytic effects. The offending stray currents may be due to earth faults on d.c. power systems, or may arise where earth returns are used on traction systems, or an earth-return signalling system exists.

In the past, protection of telephone cables has been achieved by insulating gaps or by the use of some covering over the lead sheath.

In recent years consideration has been given to forms of cathodic protection. Two types are in use, one using the primary-cell effects produced between magnesium billets, located at intervals along the cable track, and the lead sheath of the cable. The second method utilizes a mains rectifier feeding a current of anything up to 5 amp through a massive earth. The first method is suitable in areas of low earth resistivity, but the second is also practicable where the earth resistivity is high. Also, with the second method, distances of up to several miles from the massive-earth electrode system can be protected. The flow of current in either system makes the cable sheath slightly negative to earth, thus causing any stray currents to drain away via the magnesium anode or the massive earth, each of which acts as a sacrificial earth and is gradually eaten away. Unrestricted use of cathodic protection by one undertaker could cause serious corrosion in other buried plant in the same area. A committee representing interested parties has been set up to agree on the permissible conditions for the employment of such protection.

Radio and Television Interference

Radio and television interference is the aspect of the subject most in the public eye. Interference complaints received by the Post Office rose from over 82 000 in 1949 to over 141 000 in 1954. As radio and television have become such an integral part of our national life, this growth obviously cannot be allowed to go unchecked. Voluntary suppression was not achieving the necessary results, and in 1949 the Wireless Telegraphy Act was passed to permit regulations to be made to control interference. This has been followed by regulations dealing with the interference from ignition systems on motor cars, from small electric motors and from refrigerators.

An examination of trends of interference complaints received by the Post Office over the past five years reveals disturbing evidence that most sources of interference are causing increasing amounts of trouble, and the increase in the number of complaints is not merely a reflection of the increase in the listening and viewing public. The complaints are increasing at a greater rate than the number of radio and television licences. The regulations so far published only touch the fringe of the problem. A complete solution will take many years, and will require the co-operation not only of electrical engineers but of all users of electrical equipment. The elimination of interference is not solely a manufacturing problem, but is also a maintenance one.

Mr. Knox is with the General Post Office.

Abstract No. 2022
Feb. 1956

SHEFFIELD SUB-CENTRE: CHAIRMAN'S ADDRESS

By W. REWCASTLE, B.Sc., Member.

"SOME PROBLEMS ASSOCIATED WITH THE DEVELOPMENT OF THE PRIMARY DISTRIBUTION SYSTEM IN SHEFFIELD"

(ABSTRACT *of Address delivered at* SHEFFIELD, 19*th October*, 1955.)

The Sheffield primary distribution system operates at 33 000 volts a.c., 3 phase. Development began in 1934, when the load was 92 MW; 33/11 kV primary substations were established in the city to reinforce the 11 kV public distribution system, and on the premises of the larger industrial consumers to provide a bulk supply. Development of the 33 kV system has continued regularly since that time. The City of Sheffield system load is now 333 MW. By the winter of 1958–59, it is estimated that the load will exceed the firm capacity of the two existing power stations at Blackburn Meadows and Neepsend. As part of a reinforcement programme, a 132/33 kV bulk-supply point having a firm capacity of 120 MVA is being constructed. To further reinforce the 11 kV system, new primary substations will be constructed, and approximately 25 500 yd of 33 kV cable will be installed.

Primary Substations.—The standard primary substation at present adopted contains 33 kV switchgear, two 18·75 MVA 33/11 kV transformers, 11 kV switchgear and associated ancillary equipment.

The choice and acquisition of suitable sites is becoming increasingly difficult, since the urban areas are almost completely built up, and in many instances steep contours provide additional difficulties. In one of the primary substations the 18·75 MVA transformers are within 18 ft of dwelling houses, thus requiring special provision to be made to restrict noise. This site was preferred from the purely electrical distribution aspect, and although the contours were extremely bad, the choice was economically justified.

Alternative designs were prepared and submitted to the Central Authority Research Department for comment on the noise aspect of the substation design, which was a major problem. To restrict noise, so far as is possible, provision was made to build brick cells round both 18·75 MVA transformers, leaving the coolers in the open. As constructed the cells have no roofs, but these can be added should they prove to be necessary in the future. Measurements of transformer noise were made in the early hours of the morning at twenty-two test positions, before and after building the cell walls. The mean results were as tabulated below.

Noise level, dB, above background noise					
Transformer No. 1 only		Transformer No. 2 only		Transformers Nos. 1 and 2	
Before enclosure	After enclosure	Before enclosure	After enclosure	Before enclosure	After enclosure
45·6	37·8	40·0	35·6	54·3	39·2

33 kV Underground Cable System: Measurement of Cable Temperature.—There is an increasing tendency to operate cables at or near the permissible limit of temperature, by taking proper cognizance of daily load curves, and permitting loads which may be substantially in excess of published continuous ratings. This is due to:

(*a*) The necessity to defer capital expenditure for as long a period as practicable, and then to restrict the expenditure to a minimum, consistent with the provision of an adequate degree of security of supply.

(*b*) The practical difficulties of installing cables below ground in certain sections of the city, because of congestion due to other cables and other public utility works.

(*c*) De-rating, due to the proximity effect of other power cables.

Investigations, which it is hoped will provide reliable information concerning service operating temperatures, are in progress.

The "image" method of cable temperature measuring has been adopted. The equipment used consists essentially of an instrument for recording simultaneously temperatures and feeder load currents, a reference cable approximately 3 ft long, and some thermocouples.

The reference cable is a section of the feeder cable cut from a drum length during manufacture. The centre strand of copper conductor is withdrawn from each core, and replaced by a length of lightly insulated heating element.

The heating elements are connected in series with the secondary windings of current transformers, which are arranged to measure the load current of the feeder cable. The current transformer ratio and the resistances of the heating elements are selected so as to generate heat in the reference cable at the same rate as the load current generates heat in the feeder cable as a result of conductor and sheath losses.

The temperature difference between the cores and sheath of the reference cable is measured by means of differentially connected thermocouples.

Feeder-cable sheath temperatures are measured by thermocouples attached to the sheath at selected positions where it is known that hot spots will occur from consideration of cable grouping along the route, or on sections where the thermal resistivity of the ground is high.

The temperature of the feeder-cable core at a selected hot spot is obtained by connecting the thermocouple attached to the feeder-cable sheath to those attached to the reference cable. The temperature difference between the reference-cable core and sheath is thus added to the feeder-cable hot-spot sheath temperature, to provide a measure of the hot-spot core temperature. For practical purposes, dielectric losses are regarded as constant, and allowance for them is made by zero adjustment of the temperature recorder.

Ground Thermal Resistivity.—The temperature attained by the cable is dependent upon the load, the thermal resistivity of the ground in which it is laid, and the thermal capacity of the cable itself.

The thermal resistivity of the ground is a measure of the ability of the ground to conduct away the heat generated by a cable, and in consequence exercises a controlling influence on the temperature of the cable.

The method of determining the thermal resistivity of the ground by heating a buried shell was prescribed in E.R.A. Report No. F/T.128 some years ago, but for field tests to be of practical use, a quicker and less expensive method is necessary. For this purpose the "transient needle probe" method has been

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developed. This is based on work carried out by Stalhane and Pik in Sweden in 1931, and was developed by Kurtz and Mason in Canada, who described their methods in a paper published in 1952. Further investigations have been carried out by the E.R.A., who have reported on the method in Report No. F/T181, published in 1955.

An alternative method is by soil sampling and analysis. Various investigators have shown that with clay, sand, or clay-sand soil mixtures, the thermal resistivity can be assessed from a knowledge of the dry density, the moisture content, and the percentage pure sand and pure clay in the sample.

On the Sheffield system, investigations are being carried out primarily by the transient-needle-probe method, but checks are being made on the results by the soil-analysis method.

Two series of investigations have been decided upon:

(*a*) Surveys along routes selected for the installation of new cables.
(*b*) Permanently installed probes along existing cable routes, which will be used to determine and study the seasonal variation below paved roads and streets.

Investigations so far carried out indicate that the thermal resistivity of the ground is likely to be less than the normally accepted 120 thermal ohm-cm. Typical results are shown in the following table:

GROUND THERMAL RESISTIVITY, THERMAL OHM-CM

		Chippingham Street	Attercliffe	Oakes Green	Shortridge Street
Calculated thermal resistivity by soil analysis		43	46·5	58	42
Measured thermal resistivity	Y.E.B.	45	—	37	—
	E.R.A.	46	47	—	46

Paper No. 2003
Feb. 1956

SOUTH-WEST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. A. AKED, Member.

"PORTABLE EARTHS FOR H.V. OUTDOOR SUBSTATIONS: TOWER STUB CORROSION"

(ABSTRACT *of Address delivered at* GLASGOW, *5th October*, 1955.)

Design and Tests of Portable Earths for High-Voltage Outdoor Substations

The Address is largely a summary of the work accomplished by Panel "A" of the Central Electricity Authority's Area Board Chief Engineer's Conference, now published as an Engineering Recommendation.

On outdoor Grid substations, during the process of time, a considerable variety of portable earthing devices have accumulated, many of which are now considered unsuitable for the purpose, and it was with a view to improving and standardizing this equipment that the Panel was appointed.

The general requirements for a portable earth comprise a length of flexible cable with two clamps, one for fixing to the overhead conductor or busbar, and the other for fixing to the permanent substation earth. To complete the assembly, an insulating pole is required to reach the overhead busbars and fix or remove the clamp.

In designing this equipment, it is necessary to take into consideration the maximum length of operating pole, with the attached earthing cable, which could be handled by a man of normal physique in stormy weather. The clamps have to be positive in attachment, easy to operate, and, together with the cable, have to be capable of withstanding the fault current which might flow following the inadvertent energizing of an earthed circuit.

Earthing cable.—The earthing cable is essentially the heaviest part of the assembly, and it was decided that 0·1 in² circular-section copper braid was the most suitable covered with a transparent p.v.c. sheath of 0·04 in radial thickness. This is sufficiently flexible for the purpose and affords protection and the opportunity of inspection of the braid. It has a safe thermal capacity and has been tested to withstand 13·1 kA for a period of 2 sec. It is recommended for systems where the maximum sustained fault current is not in excess of this figure, i.e.

250 MVA at 11 kV
750 MVA at 33 kV
2 500 MVA at 132 kV

If the sustained fault is calculated to be in excess of this figure, it is advisable to apply a supplementary set of earth leads.

The earthing cable is composed of circular-section copper braid, comprising 4 concentric leads each of 4 braids having 24 smaller braids of ten 0·012 in² plain copper wires.

Operating pole.—Twelve feet is the maximum length which can be handled by a man of normal physique. At many substations, however, an 8 ft pole is generally suitable, so the recommended pole comprises an 8 ft length with a 4 ft extension, which can be added when necessary but is designed so that it cannot be used to apply the conductor clamp.

The pole should be of seasoned ash of 1⅜ in diameter or hollow spruce of 1½ in diameter with solid ends.

Clamps.—The main design of clamp is suitable for attachment to circular conductors or busbars, from 0·25 in to 1·5 in diameter, positive screw type. It is detachable and is operated by a bayonet-fitting tightening screw. When closed it will embrace more than 180° of the conductor or busbar surface. The clamp is of bronze and has successfully withstood the fault-current tests.

The earth clamp recommended is suitable for attachment to flat strip of thickness not exceeding ½ in or to round stranded conductor of 0·05 in minimum section. The jaw contacts have two parallel ribs with a shallow groove between them, giving two high-pressure line contacts on flat strip or non-deforming screw pressure on a circular conductor.

Mr. Aked is with the South of Scotland Electricity Board.

Tests.—The apparatus was tested, with the following results:

Test No.		1	2	3	4	5
Average symmetrical through current	kA	13·6	15·0	17·5	23·0	23·6
Duration of above ..	sec	2·36	1·6	3·0	2·1	2·75
Peak current ..	kA	32·0	39·0	36·0	52·5	54·0

Test No. 1.—Using a 3-phase set of single 0·1 in² earthing cables with line and earth end clamps.
The cables fused at 2·36 sec, but there was no burning of the clamps.
Test No. 2.—As (1).
Cable sheath melted off but no burning of clamps.
Test No. 3.—As (1), but with two phases connected to heavy test cables and one phase to two 0·1 in² earthing leads in parallel.
Slight smoking of sheaths but no burning of clamps.
Test No. 4.—As (3), using two new earthing cables.
Cable fused at 2·1 sec owing to small break in one of the fittings.
No burning of clamps.
Test No. 5.—As (4), but with heavy cables throughout.
No burning or loosening of clamps.

Tower Stub Corrosion

The tower stub is that portion forming the base of the tower leg, erected largely below ground level. In some designs the complete stub is encased in concrete from the foundation upwards. In others the steelwork is bare and in contact with the soil.

The necessity of investigating the corrosion of tower stubs became apparent when a tower on the Greenock–Saltcoats 132 kV line fell over on its side during a strong gale, owing to the fracture of two stub members which had corroded very badly.

In general, corrosion occurs only where there is direct contact with the surrounding earth, but it has been found that where a joint occurs in the concrete there can be corrosion if the joint has not been properly made and sealed. In the construction of Grid towers the concrete chimney is brought up to ground level, and at a later date a concrete muff is placed on top to round off the sharp edges and distribute such rain water as may run down the tower legs. Owing to ground contours, the joint between the chimney and the muff often came below ground level. If the joint was not properly made corrosion was frequently evident. In other cases, where the ground contour varied, the muff was placed at ground level without bringing the chimney any higher, and as a consequence there was an exposed length of steelwork below ground which was usually subject to corrosion.

At the time, it was considered that the corrosion was due to electrolytic action, and an investigation was made using a half-cell electrode (copper/copper-sulphate). The difference of potential between the half-cell electrode and the tower-stub steelwork was expected to give some idea of the oxidation of the steelwork.

Although numerous readings were taken using this half-cell, the results obtained appeared to bear no relationship to the condition of the stubs when these had been exposed for examination. Graphs were drawn for a complete series of readings on various lines, indicating the positions where corrosion was evident. From these curves it appeared that with both anodic and cathodic readings corrosion was present.

It is thought that the lack of relationship between the readings and the actual findings may have been due to the fact that no account was taken of the pH-value, resistivity and moisture content of the soil. In certain earth conditions, such as water-logged clay, corrosion can be caused by the presence of sulphate-reducing bacteria, and this possibility was not overlooked.

Other methods of determining the extent of stub corrosion have been devised, but they have not been tried on a sufficient number of towers to prove their reliability.

Abstract No. 1995
Feb. 1956

TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. HIGSON, Member.

"ELECTRICITY IN THE EXPANSION OF THE IRON AND STEEL INDUSTRY"

(ABSTRACT *of Address delivered at* MIDDLESBROUGH, *5th October*, 1955.)

The demand for increased production of iron and steel to about 20 million tons per annum has created many problems for the electrical engineer. New plants have had to be designed and built, but existing plants have had to be kept in commission and extended.

Considerable work has had to be done on the provision of adequate electrical distribution systems. In order to investigate the various alternative schemes rapidly we have built a d.c. system calculator. The design is based on the well-known method of conversion of percentage reactance to resistance, in which the reactance of all circuit-elements is expressed as a percentage to a common base. This calculator has 30 elements and is surrounded by six sectionalized busbars for convenience, thus avoiding an untidy array of wires in front of the panel. The equipment can be rapidly set up, and the fault level of any busbar on the system under check and the contribution from any generator or in-feed can be established. This has saved considerable time in slide-rule calculations and provides a minimum of slide-rule accuracy.

The selection of the correct size of conductor in a cable for a given load is a simple matter, but when the choice is reviewed in the light of fault conditions the limitation of 120° C total temperature recommended by the cable manufacturers for paper cables causes a much larger size cable to be installed. Investigations show that the paper-insulated cable could be taken to more than 120° C for a short time if there was no danger arising from the approach to the melting-point of solder used in cable lugs, joints, etc. An alternative type of connector having the inherent advantages of the solder joint but without the low melting-point could result in some economy in cable distribution schemes.

Some of the largest electric drives on reversing rolling-mills in this country were installed about 30 years ago. Troubles now being experienced on these old machines are principally due to defective insulation and loose cores, whilst some Ilgner-set generators with long commutators have given trouble due to crystallization of commutator bars. In one or two cases new armatures have been fitted to avoid long shut-down periods for rewinding and repairs, whilst others have had their armatures rewound during the annual holiday period of 14 days. Amplidyne control has been fitted to some of these mill drives in order to obtain faster operation, working right up to the current limit.

A contributory cause of the insulation troubles has been the inefficiency of the earlier air-cleaning equipments, with consequent accumulation of dirt inside the machines causing tracking and

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the choking of ventilating ducts. Many alternative ventilating schemes have been investigated, and for one mill in a dirty situation we have adopted a totally-enclosed recirculating system using both viscous and precipitation cleaning units in series for the make-up air, and evaporative coolers for the cooling water in the air coolers; this will give a maximum degree of cleanliness and will occupy only a relatively small space.

The use of separate motor drives to the top and bottom rolls on blooming and slabbing mills introduces problems of peripheral-speed matching of the rolls and torque matching of the motors over the whole of the speed range. This is achieved by comparing tacho-generator voltages from each motor and the current in each armature and feeding these differences into amplifiers which regulate the generator and motor exciters.

More complicated problems arise on reversing drives where there are two mill stands with hot metal in both stands together. In this case, both mills must run together, either with speed matching or with a speed difference which varies according to the amount of reduction per stand, the relative roll diameters and the direction of rotation.

The method of overcoming these problems is too lengthy to describe in this abstract.

Modern high-speed rod mills with closely coupled stands and multiple motor drives introduce considerable problems on speed matching, but are otherwise straightforward.

An iron and steel works requires a large variety of motor drives:

(*a*) Constant speed for fans, pumps, etc., where the squirrel-cage motor is supreme. We have also used high-torque squirrel-cage motors for conveyor drives and have found them to be completely satisfactory with direct-on-line starting even for very long conveyors.

(*b*) Reversing motors for cranes, roller tables, etc., are usually one-hour-rated mill-type motors which can be either a.c. or d.c. We have several hundred a.c. motors, some of which perform at the rate of up to 500 reversals per hour, but the a.c. machine compares unfavourably with the d.c. machine for this duty because of higher inertia, low power factor, lower r.m.s. duty cycle, lower efficiency and difficulty of speed control on light loads.

The tendency to-day for high-speed reversal duty is to use Ward Leonard driven d.c. motors with current limit control up to $2\frac{1}{2}$ times full load. These motors are 230 volt with voltage control up to 460 volts, thus giving twice the rated h.p. at twice the rated speed, the only increase of electrical losses being in the iron circuit.

D.C. injection braking is used on large a.c. slip-ring machines in several cases, particularly for rapid deceleration of the very large motor-generator sets used on the main drive equipments.

Safety First

A large number of accidents have occurred in the past due to men making contact with crane conductors.

We have tried out a variety of arrangements to supply the moving portion of the crane without exposed conductors; amongst these is one in which a 4-core $0 \cdot 4\,\mathrm{in}^2$ Neoprene cable, about 3 in in diameter, is used on a coiling drum, 9 ft in diameter, to cover the long travel drive of about 100 yd on a stripper crane. This arrangement has proved to be quite satisfactory but has its limitations in the amount of long travel cable which can be accommodated. The cross-travel connections in this case are loops of cable from a mast erected mid-way in the span, connected at the other end to the moving bogie on the crane. Other cranes have been fitted with various other arrangements including reeling drums, Coburn tracks with looped cable, etc., and the results so far are encouraging.

We have adopted a system of high mast lighting for our railway marshalling yards. Railway grids up to 1 800 ft long by 500 ft wide can be satisfactorily illuminated at moonlight level by means of floodlight fittings mounted at the top of 150 ft masts. The designed level of illumination was a minimum intensity at any point between two towers of 0·03 ft-candle; we find that this level is quite satisfactory to show up obstructions and to handle the traffic. We have found that in fog this type of lighting is superior to a large number of low masts with localized lighting.

Modern electronic techniques are being applied in many ways, including precision control, communications, etc.; experimental work with industrial television equipment has given promising results; and there is no doubt that considerable progress is being made towards automation.

It is too early to say just what effects the developments in nuclear fission will have on the iron and steel industry, but it is essential for the progress in this field to be kept under constant review to see just where it can be applied.

Abstract No. 2000
Feb. 1956

NORTH-EASTERN RADIO AND MEASUREMENTS GROUP: CHAIRMAN'S ADDRESS

By C. H. W. LACKEY, B.Sc., Member.

"SOME MEASUREMENTS IN CIRCUIT-BREAKER RESEARCH AND TESTING"

(ABSTRACT *of Address delivered at* NEWCASTLE UPON TYNE, 17*th October*, 1955.)

Measurements in circuit-breaker research and testing are almost entirely of transient phenomena, e.g. transient voltages and currents, pressure pulses and sudden mechanical movements. It follows that measuring equipment used for this purpose must usually be automatic in operation and closely co-ordinated with the operation of the circuit-breaker being tested. The amplitudes of the measured quantities may vary widely between tests, and in research work especially, random phenomena occasionally arise which are difficult to repeat. A very high degree of first-shot reliability is therefore required of these measurements, and great care must be taken in the setting and organization of the equipment so as to ensure that nothing of importance can be missed in any test.

In the sphere of mechanical measurements, the velocities of moving contact structures and their associated mechanisms are of first importance because of the major influence which such movements have on the electrical performance of a circuit-breaker, and also as a means of determining the accelerating and decelerating forces which arise. Of the various devices used for this purpose the rotating-drum apparatus, in which a brass

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stylus, connected to the moving part, draws a curve of the movement on specially prepared paper carried by the drum, is extensively used for routine work. Where co-ordination with oscillograph records is required, the cylinder and stylus are replaced by a variable resistor connected in a strip circuit. For measuring the movements of parts of small mass, a miniature recorder comprising an eccentrically mounted rotating armature in combination with an inductance bridge is used. Complicated mechanical movements, relative movements of linkages and the like, and arc movements are best measured by high-speed ciné cameras with a framing rate of up to 2 000 frames per second. For very-high-speed movements an ultra-high-speed camera with a framing rate of up to 600 000 frames per second has been developed.

A major research problem is the measurement of currents very near to current zero, especially post-zero currents. Satisfactory results have been obtained with specially designed shunts and amplifiers, and also with the relatively simple though slightly indirect rate-of-change-of-current method, in which the voltage across an inductance is measured. In the latter method, problems of shunt inductance and amplifier design are eliminated.

For the measurement of the natural frequencies of short-circuit testing-station circuits, the restriking-voltage indicator has proved a useful tool, and recent advances in its design should widen the scope of its application. In combination with a specially designed network analyser, this instrument has given valuable data on the restriking transients of electrical power systems.

The pressure of the oil and of the gas bubble in an oil circuit-breaker presents important measuring problems, the solution to most of which is found in electromagnetic recorders working on the change of magnetic reluctance resulting from the deflection of a diaphragm. When measuring the pressure pulses arising from capacitance switching, the recorder must have a very high speed of response and be small enough to be accommodated inside an arc-control device without affecting the characteristics of the device in any way. It must also be carefully shielded against the effects of high values of magnetic and electric flux. Special recording devices have been developed for this purpose.

The performance of multi-break circuit-breakers is greatly influenced by the voltage distribution between the breaks, and tests must be devised to check this. The electrolytic-tank has proved a valuable means of measuring voltage distribution, especially in the design stage of a circuit-breaker. Subsequent high-voltage and high-power tests have shown very good agreement with electrolytic-tank measurements.

Abstract No. 1985
Feb. 1956

WESTERN SUPPLY GROUP: CHAIRMAN'S ADDRESS

By E. K. WOOD, Associate Member.

(ABSTRACT *of Address delivered at* CARDIFF, 17*th October*, 1955.)

As practically all the formal and informal papers read before the Western Supply Group concern design or research either at the manufacturing source or the ultimate site, the Address introduced some of the major problems in the actual manufacture of equipment and its transport to site.

Taking as an example steam turbines and generators, the production from all sources in Great Britain has approximately trebled since the war. This in itself has necessitated considerable increases in factory space and labour, the latter requiring very careful attention to such matters as housing and comprehensive apprenticeship schemes.

Within the factory the greatest change has come with the increased sizes of equipment, and diagrams were given showing typical changes since the war of, for instance, steam-turbine alternators where the weight has increased from 103 to 226 tons, transformers from 60 to 155 tons and the waterwheel alternators from 225 to 1 040 tons. The increased dimensions of the items being manufactured affected machine tools, ovens, annealing furnaces, cranage and general design of the shops, particularly the erection and testing bays.

An example was given of a 50 ft boring machine turning a waterwheel alternator stator 42 ft in diameter, and a boring machine capable of taking pieces up to 80 ft in diameter is being installed. A figure of £200 000 was quoted as the cost of the 50 ft boring machine together with foundations. If to this is added the cost of the other machine tools required—the ovens, stress-relieving furnaces, buildings, cranes, etc.—a very large figure is obtained before the supply industry can construct the larger and more efficient power stations.

The Address dealt in some detail with the problems of transporting the large items of equipment now being manufactured, and emphasized the fact that any gross weight of 150 tons or over (equivalent net weight of approximately 100 tons) requires a special order from the Ministry of Transport. Before being granted, the matter has to go through the legal and routing sections of the Ministry who, in turn, consult local highway and bridge authorities over the entire proposed route. Such an investigation takes many months to complete, and the full co-operation of the manufacturer and user is necessary in order to avoid unnecessary requests for special orders, otherwise the Ministry's limited department would not be able to meet the demand. As an example, temporary storage involving two special licences should be avoided at all costs.

Reference was made to methods of packing for shipment, particularly the modern method of "cocooning." This involves covering the entire item with a plastic protective coating which is sprayed on to and completely seals the item of equipment.

A tribute was paid to the teams of erection engineers on site, and an appeal was made for storage areas and cranage to be made available and civil engineering work to be sufficiently advanced so that the erection of equipment can be carried out on similar lines to a well-run factory.

Following the Address, films of transporting heavy equipment mainly in the South Wales area were shown, including one made by the South Wales Division of the Central Electricity Authority of a 60 MW stator being moved from Abergavenny to Carmarthen Bay power station.

Mr. Wood is with the English Electric Co., Ltd.

DISCUSSION ON

"A SHORT MODERN REVIEW OF FUNDAMENTAL ELECTROMAGNETIC THEORY"*

Mr. C. Hargreaves (*communicated*): The equation for the induced e.m.f. is given by the author [eqn. (22)] as

$$\text{e.m.f.} = -\iint\left[\frac{\partial B}{\partial t} - \text{curl}\,(uxB)\right]da$$

This equation is relied on by mathematical physicists and is thought to be quite general in its application and equivalent to the eqn. (14), e.m.f. $= -\dfrac{d}{dt}\iint Bda$ or e.m.f. $= -\,d\phi/dt$, from which it is derived as stated by the author.

Now, if these expressions are truly equivalent they ought to give the same result in any particular application, including an expanding rectangular circuit supplied by a constant current.

The magnetic field is therefore set up by the current in the circuit itself and not by an external uniform field, as in Fig. 7 and in textbook treatments, which are mainly concerned with making it appear that "flux cutting" gives the same result as the "change of flux" theory. I agree with the author when he says that examples which would prove that this is not always so are generally avoided.

Therefore some consideration should be given to the expanding rectangle which does not lie in a uniform field. If eqns. (22) and (14) are equivalent they ought to give the same algebraic expressions for the induced e.m.f.

I have considered this problem and have made detailed calculations, the results of which are as follows:

(*a*) From e.m.f. $= -\dfrac{d\phi}{dt}$

we get

$$\text{e.m.f.} = -4iv\left[\log_\varepsilon\frac{s}{g} + \log_\varepsilon\frac{\sqrt{(L^2+g^2)}+L}{\sqrt{(L^2+s^2)}+L} + \frac{L^2+s^2}{L} - 1\right]$$

(*b*) From the equation e.m.f. $= -\,i\dfrac{dL}{dt}$ we obtain the same expression as in (*a*).

where L is the inductance of rectangle, shown in Fig. F.

(*c*) The e.m.f. calculated from the rate of flux-cutting, owing to conductor CD moving to the right, is

$$-\,2iv\left[\log_\varepsilon\frac{s}{g} + \log_\varepsilon\frac{\sqrt{(L^2+g^2)}+L}{\sqrt{(L^2+s^2)}+L} + \frac{\sqrt{(L^2+s^2)}}{L} - 1\right]$$

i.e. exactly one-half of the previous result. The minus sign prefixing this expression is to show that this e.m.f., like the previous one, acts in the opposite direction to the current flow. In these expressions

L and s = Dimensions of the rectangle.
$g = 0{\cdot}778\,8r$, where r is the radius of the conductor.
v = Velocity of conductor CD, cm/sec.
and i = Current, c.g.s. electromagnetic units.

The e.m.f. will be given in the same system of units.

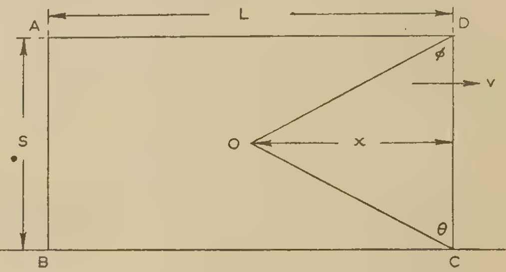

Fig. F

(*d*) We see that if eqn. (22) is to give the same result as eqn. (14), the surface integral of $-\partial\boldsymbol{B}/\partial t$ should give an expression identical to the one given by flux cutting in (*c*). We find, however, that at any point O, inside the rectangle, $\partial\boldsymbol{B}/\partial t$ is negative and given by the equation

$$\frac{\partial B}{\partial t} = -\frac{iv}{x^2}(\cos\phi + \cos\theta)$$

The surface integral of $-\partial\boldsymbol{B}/\partial t$ is given by

$$2iv\left\{\log_\varepsilon\frac{\sqrt{[(L-r)^2+(s-r)^2]}+(L-r)}{\sqrt{[r^2+(s-r)^2]}+r} - \log\frac{\sqrt{[(L-r)^2+r^2]}+(L-r)}{r(1+\sqrt{2})} - \sqrt{\left[1+\left(\frac{s-r}{L-r}\right)^2\right]} + \sqrt{\left[1+\left(\frac{r}{L-r}\right)^2\right]} + \sqrt{\left[1+\left(\frac{s-r}{r}\right)^2\right]} - \sqrt{2}\right\}$$

which is clearly not identical to the expression in (*c*). It should be noted that the surface integral of $-\partial\boldsymbol{B}/\partial t$ gives an e.m.f. which acts in the same direction as the current, thus contradicting Lenz's law.

This is because, inside the rectangle, $\boldsymbol{B}$ is decreasing everywhere as the circuit expands; therefore $\partial\boldsymbol{B}/\partial t$ is negative and $-\partial\boldsymbol{B}/\partial t$ is positive everywhere inside the circuit. Consequently, the surface integral of $-\partial\boldsymbol{B}/\partial t$ is positive; it therefore gives not only the wrong magnitude for the e.m.f. but also the wrong direction.

It appears, therefore, that eqn. (22) is not equivalent to eqn. (14). Furthermore, eqn. (22) cannot be relied upon as a general formula for the calculation of e.m.f.

Mr. P. Hammond (*in reply*): The case of the rectangular circuit discussed by Mr. Hargreaves is full of interest. In this case the magnetic flux arises from the current in the circuit itself, and this circuit is undergoing a change in configuration. It thus becomes essential to include the flux within the material of the conductors in the calculation. It seems to me that Mr. Hargreaves has omitted this flux and this has given him the misleading result that the flux density is decreasing everywhere within the circuit. Actually $\boldsymbol{B}$ is increasing and eqn. (22) gives the correct answer. But it would be fair to admit that eqn. (22) is clumsy in its application to this particular case.

* Hammond, P.: Paper No. 1595, December, 1953 (see 101, Part I, p. 147).

621.318.1 : 538.2

Paper No. 1947
Feb. 1956

FERROMAGNETISM IN RELATION TO ENGINEERING MAGNETIC MATERIALS

A Review of Progress

By Professor F. BRAILSFORD, Ph.D., B.Sc.(Eng.), Wh.Sc., Member.

SUMMARY

After a brief introductory account of the earlier development of the subject of ferromagnetism a review is given of theoretical and experimental work mainly within the past ten years. This includes an account of ferromagnetic domains and of the small-particle theory of high coercivity. A description of the ferrites and of ferrimagnetism is given, and this is followed by a discussion of recent observations and ideas on the magnetic phenomena occurring at frequencies up into the microwave region.

(1) INTRODUCTION

The theory of ferromagnetism, in its finer detail, continues to offer many hard problems to the physicist and mathematician. A discussion of the outstanding difficulties would take the engineer into deep water. But in spite of some obscurities there exists a satisfying general picture of the subject, which has, in fact, been illuminated in the past ten years by notable theoretical and experimental work. Some of this work clearly discloses the underlying macroscopic structure of ferromagnetic materials.

During this period also new magnetic phenomena occurring at high frequencies have been observed in the ferromagnetic metals and in that increasingly important class of engineering magnetic materials known as the ferrites. The ferrites are magnetic oxide materials having exceedingly high electrical resistivity, so that even at the highest frequencies, eddy-current effects are relatively unimportant. Their properties and behaviour have been explained by Néel, Kittel and others, and their usefulness extends into the microwave region.

It is an object of this review to discuss these developments in simple terms.

Ferromagnetic theory began with Ampère, who proposed that there was no magnetism except that due to electric currents. The molecules of a magnetic material contained permanently-circulating currents which gave to each a magnetic moment. A change in magnetization was then accompanied by rearrangements of the magnetic axes of the molecules.

Ewing represented the molecular magnets by arrays of pivoted compass needles and sought to show that the magnetic behaviour of a ferromagnetic material like iron was governed by the interacting magnetic forces of the magnets upon one another. Ewing's models were qualitatively successful, but, quantitatively, when the now-known values of the molecular or atomic magnets and their spacings in the crystal lattice are employed in calculations, the theory fails completely. If the ferromagnetism of iron were due only to the forces envisaged by Ewing it would have a coercivity, for example, too high by a factor of the order of 10^5.

Langevin, in 1905, gave the first quantitative treatment of magnetization in actual materials. Accepting the idea of molecular magnets, Langevin disregarded the magnetic forces between them but took account of their relatively violent thermal motions. When a magnetic field is applied to such an assemblage of magnets the ordering action of the field is opposed by the disordering action of thermal agitation. Following Maxwell and Boltzmann, Langevin solved this problem using statistical kinetic theory. Magnetization curves could now be calculated in terms of the molecular magnetic moment and temperature of the material. Langevin's analysis was a great contribution to the theory of paramagnetism, but still failed to account for the extraordinary properties of iron and other ferromagnetic materials.

According to the Langevin theory a field strength of about 10^7 oersteds would be required to produce magnetic saturation in a sample of iron. This is too great by a factor of the order of 10^4. Weiss, in 1907, postulated that in a ferromagnetic material a high "molecular field" of unspecified origin existed, giving spontaneous saturation. He further supposed that the material was subdivided into "domains," the directions of the saturation vectors varying in the different domains. A random distribution of the domain vectors thus would make the apparent bulk magnetization of the specimen zero, and rearrangements of the vectors under the action of an applied field would give the observed magnetization characteristics of the material. The combination of the Langevin and Weiss theories was immediately successful in correlating many experimental observations with calculation, and the domain theory is now well established.

The idea of domains suggests that magnetization may increase or decrease, not smoothly, but with discrete steps. The first experimental evidence for this was due to Barkhausen[1] in 1919. A rustling noise may be heard, under quiet conditions, in telephones connected to a search coil embracing a ferromagnetic specimen in which the magnetization is changing, owing to the impulses of e.m.f. induced by the successive discontinuities. Bozorth and Dillinger[2] in 1930 measured the amplitudes of the impulses for a number of ferromagnetic materials. On the assumption that the individual impulses were associated with whole domains, they estimated the domain volumes and found that the largest had linear dimensions of about $0\cdot003$ cm, corresponding to about 10^{15} atoms. More recent work which will be described shows, however, that domain sizes are, in general, much greater than this. The Barkhausen jumps are, in fact, to be associated with the discrete movements of the boundary surfaces between domains sweeping out only fractional domain volumes.

On the basis of the Langevin–Weiss theory modified a little by quantum theory, and using numerical values determined experimentally, it is possible to estimate the magnitude of the internal Weiss molecular field. For iron at 20° C this turns out to be equivalent to approximately 7×10^6 oersteds ($5\cdot5 \times 10^6$ amp/cm). Some explanation of the origin of this truly enormous field strength has been given by the mathematical physicists. In the Bohr model of the extranuclear structure of atoms there are electrons moving in orbits about a central nucleus. From spectroscopic data it is also concluded that each electron is spinning about its own axis like a top. Both the orbital and gyroscopic motions of the electron charge constitute circuital currents and hence they provide components of magnetic moment. This recalls Ampère's hypothesis about the origin of magnetism, which has already been mentioned. In general, the

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electrons are in pairs spinning about parallel axes in opposite directions, and so making the resultant spin moment zero. In fact, in the diamagnetic elements the resultant magnetic moment for all the orbital and spin motions is zero. In the others, where there are unpaired outer electrons the atom as a whole has a magnetic moment. From the spectroscopic data already mentioned in conjunction with the results of certain magneto-mechanical experiments on ferromagnetic specimens it is concluded that the carriers of the effective magnetic moment of the atom are these excess spinning electrons. The orbital motions are believed to contribute only a small part, perhaps about 10%, to the total amount. The Weiss field is now supposed to be the result of strong quantum-mechanical forces of interaction between the spinning electrons in the neighbouring atoms of the material. The mathematical difficulties associated with a rigid solution of this problem appear to be insuperable. It seems, however, that in ferromagnetic materials the forces of interaction are positive, meaning that the spinning electrons responsible for the atomic magnetic moment in atoms which are nearest neighbours are held with parallel axes and spins in the same direction, thus imparting magnetic saturation over the whole volume which is one domain. For this to be the case it has been suggested that the ratio of atom spacing to atom diameter must be more than about 1·5, as, indeed, it is for iron, cobalt, nickel and gadolinium. On the other hand, it is possible for the forces of interaction to be strongly negative, in which case the spins in each atom are firmly held on parallel axes but with a direction of spin opposite to that of the nearest-neighbour atoms. There is thus a domain structure again in this case, but the domain magnetization is zero and the material is said to be antiferromagnetic.

Ferromagnetic materials are crystalline, and it has been established that the equilibrium positions of the domain vectors are related to particular crystallographic directions. For example, iron has a body-centred cubic crystal structure and the domain vectors will normally lie parallel with cube-edge directions of the crystal. The conditions are different in nickel, which is face-centred cubic, and different again in cobalt, which has a hexagonal structure. Some account of this has been given in the previous review,[3] and a fuller account is to be found in a number of recent books.[4,5,6]

(2) THE GEOMETRY OF DOMAINS

(2.1) Theoretical Aspects

The subject of the domain structure of ferromagnetics has been advanced in recent years by the great theoretical contributions of Néel[7,8,9] and by subsequent confirmatory experimental work, notably that in America. Any system of self-saturated domains in, for example, a piece of iron will have energy associated with it. This energy may be split into a number of independent components arising in different ways inside the metal. In the absence of an externally-applied field Néel showed that a condition of equilibrium, when the sum of these energy components was a minimum, would be attained when the domains had certain particular sizes and geometrical configurations. The expected shapes have, in fact, since been found to occur, and with suitable techniques they may be mapped and viewed under the microscope. To understand the observed patterns it is necessary to consider briefly the energy components just mentioned.

Fig. 1(a) shows how the atoms are arranged in a crystal of iron. Each atom has a magnetic moment and the atomic magnetic axes lie parallel with one another in each domain, owing to the Weiss field giving spontaneous magnetic saturation in one direction. It is known from experimental work on crystals that, with no applied field and in the absence of other complications

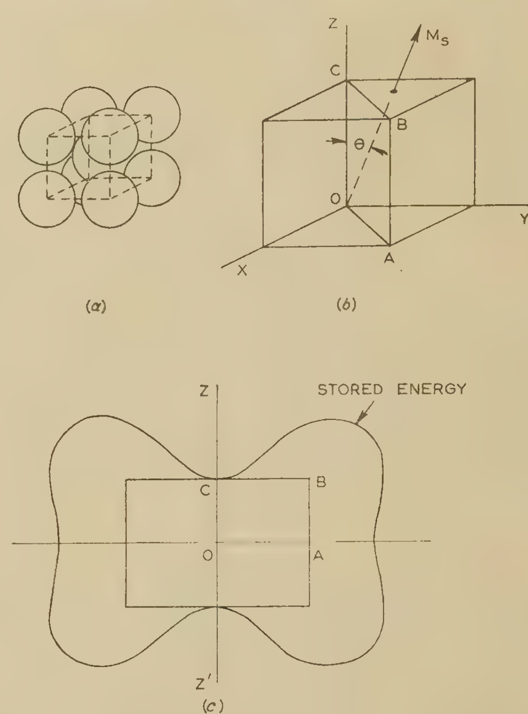

Fig. 1.—Energy of magnetic anisotropy in a domain of iron.

such as strong internal mechanical stresses, the direction of the saturation intensity of magnetization, M_s, in iron will be parallel with a cube edge of the crystal. There are six equally possible directions, since the crystal has cubic symmetry, corresponding to the co-ordinate axes—positive and negative—shown in Fig. 1(b). To rotate the vector M_s away from the cube-edge direction, as shown in Fig. 1(b), experimental observation indicates that work must be done. Energy would in this case be stored in the crystal, on account of the crystalline forces acting to restore M_s to a cube-edge direction. Detailed knowledge on the atomic scale is not available to enable a satisfactory explanation of the origin of these forces to be given. They are an experimental fact. If now the vector M_s were made to rotate in the diagonal plane OABC, this stored energy of magnetic anisotropy in the domain would vary according to a polar diagram of the form shown in Fig. 1(c). This is one of the components of energy just mentioned, and it is a minimum when M_s lies along any cube-edge direction of the crystal lattice.

The second component is the magnetostatic or demagnetization energy. The body shown in Fig. 2(a) is assumed to be uniformly magnetized with an intensity M. Induced magnetic poles indicated by the positive and negative signs will appear on the surface as shown, and these produce, not only an external field in the direction of the arrows, but also a reverse or demagnetizing field H_d inside the body. If the body is ellipsoidal in form and M lies along an axis, H_d is uniform and parallel with the axis. In fact, $H_d = -N_dM$, where N_d is the demagnetizing factor which depends upon the proportions of the ellipsoid. To increase M work must be done, since this increase must be made against the opposing demagnetizing field. The system therefore has energy stored in it, on account of its shape, if M is in some way maintained, and this is easily shown to be $\frac{1}{2}N_dM^2$ per unit volume of the body. This magnetostatic energy is thus proportional to N_d. A sphere is a special case of the ellipsoid and in this case $N_d = 1/3\mu_0$ (M.K.S. units: $\mu_0 = 4\pi \times 10^{-7}$ H/m). However, N_d has its maximum value $1/\mu_0$ for a thin flat plate magnetized normally to the surfaces, as shown in Fig. 2(c).

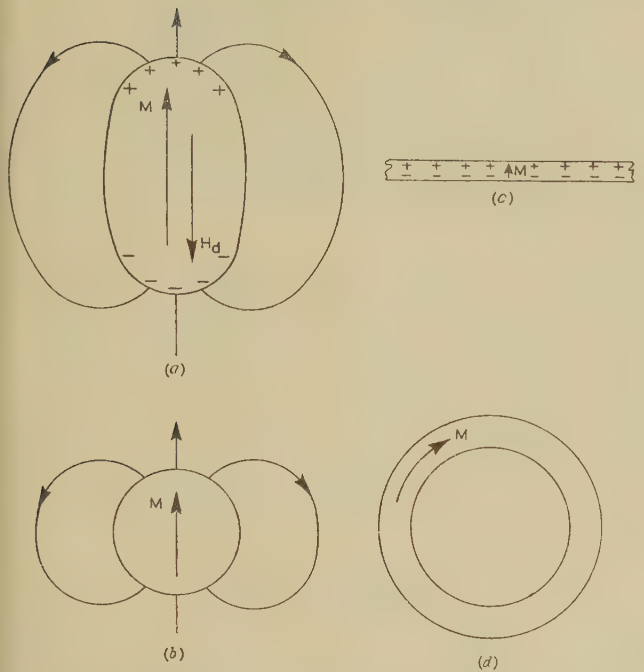

Fig. 2.—Magnetostatic energy or energy of demagnetization.

(a) Ellipsoid.
(b) Sphere, $N_d = 1/3\mu_0$.
(c) Flat plate, $N_d = 1/\mu_0$.
(d) Closed circuit, $N_d = 0$.

A little consideration shows that there is now no field external to the plate, so that the magnetostatic energy resides inside the material itself. This is a useful concept, especially when considering finite domains embedded in surrounding material also made up of domains. If, on the other hand, the ellipsoid is greatly elongated in the direction of M, the demagnetizing factor decreases and the magnetostatic energy becomes small. Again, if the magnetic circuit is closed on itself, as shown in Fig. 2(*d*), there is nowhere any free pole, H_d and N_d are zero and the magnetostatic energy is also zero.

Suppose now that the rectangular block[10] shown in Fig. 3 is a single crystal of iron with the edges parallel to the crystallographic cube-edges. If this block were a single domain as depicted in Fig. 3(*a*), the saturation magnetization would lie parallel with a cube-edge direction, since this would make the energy of magnetic anisotropy a minimum. Such a block having an intensity of magnetization M_s equal to the saturation value for iron would be a permanent magnet stronger than could be made from any permanent-magnet material. However, free poles would appear on the ends of the block, and so it would have a high magnetostatic energy for the reasons already given. The block might, however, be subdivided into two equal domains, as shown in Fig. 2(*b*). The energy of magnetic anisotropy and the intensity of magnetization are unchanged, but now half of the free pole at each end has been reversed in sign and hence the internal demagnetizing field has been reduced. The magnetostatic energy in Fig. 3(*b*) is therefore lower than that in Fig. 3(*a*). This may be seen in another way. To restore the condition shown in Fig. 3(*b*) to that in 3(*a*), and allowing the block to be in two pieces, the two domain magnets in Fig. 3(*b*) might be pulled apart. Because of the attraction between them work would have to be done. If now one half were reversed and the halves reunited to give condition shown in Fig. 3(*a*), still more work would be done to overcome their repulsion: the condition shown in Fig. 3(*b*) is therefore obviously one of lower

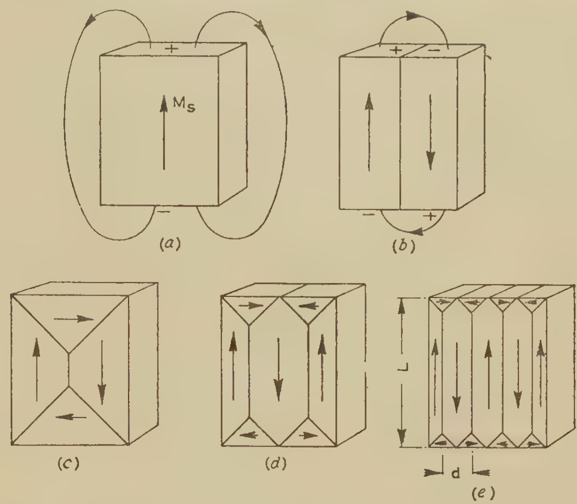

Fig. 3.—Subdivision of a domain to reduce stored energy (Néel: Williams).

(a)–(c) Reducing magnetostatic energy.
(d), (e) Reducing magnetostrictive-strain energy.

magnetostatic energy than that in Fig. 3(*a*). But the magnetostatic energy could be reduced to zero without changing the anisotropic energy if the block were composed of four domains, as shown in Fig. 3(*c*). The required condition, with domain vectors at right angles, is that the intervening boundary surface shall be at 45° to each vector, so that the normal component of magnetization on either side of the boundary is the same—$M_s/\sqrt{2}$ in this case. There is now a closed magnetic circuit with no free pole at any point, corresponding, in fact, to the condition shown in Fig. 2(*d*). The magnetostatic energy is eliminated.

The condition shown in Fig. 3(*c*), however, introduces a third component of energy important in ferromagnetic theory. As early as 1847 Joule found that the length of an iron rod increased when it was magnetized. A number of other effects involving dimensional changes on magnetization in ferromagnetic materials have since been observed, the name magnetostriction embracing them all. From measurements on single crystals it is inferred that in an iron domain the otherwise cubic crystal structure is very slightly distorted. The length along a cube edge in the direction of M_s is extended by an amount λ_s, the saturation magnetostriction, where λ_s is about 20 parts in a million. At the same time there is a lateral contraction of about $\lambda_s/2$. Hence when the upper and lower domains form in Fig. 3(*c*), the lattice structure in these domains would extend in the horizontal direction, if free to do so, by an amount $(3/2)\lambda_s$. A mechanical restraint is obviously placed on this movement in the solid block, and although a change in the domain formation from the condition shown in Fig. 3(*b*) to that shown in Fig. 3(*c*) eliminates the magnetostatic energy, a component of magnetostrictive-strain energy is now introduced. If the volume of the strain-producing horizontal domains can be reduced, this component of stored energy is also reduced. This occurs when the domain arrangement changes from that shown in Fig. 3(*c*) to that shown in Fig. 3(*d*) and again from that shown in Fig. 3(*d*) to that shown in Fig. 3(*e*). The wedge-shape domains at the ends of the block are called "closure domains." Their total volume becomes smaller as the vertical domain boundary surfaces come closer together, thus forming thin plane domains like the pages of a book. A limit to this laminating process, however, arises when a fourth source of internal energy becomes important. This is the energy associated with the domain boundaries themselves, and

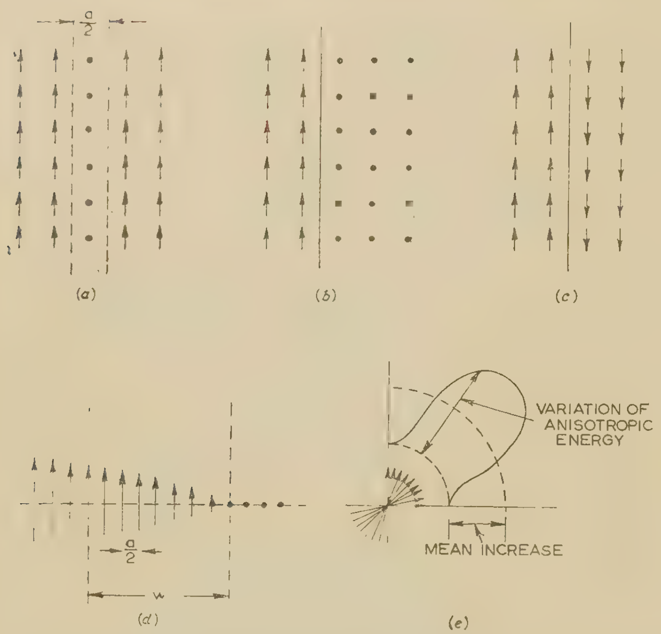

Fig. 4.—Domain boundaries.

(a) One layer of atoms twisted through 90°.
(b), (c) 90° and 180° boundaries, respectively, with sharp transition.
(d) 90° boundary of finite wall thickness.
(e) Variation of anisotropic energy in a 90° boundary.

this energy component in the block increases as more and more boundary surfaces are introduced.

The origin of the boundary energy may be made clear by means of Fig. 4, in which the arrows represent the magnetic axes of the atoms in, for example, an iron crystal. In Fig. 4(*a*) it is assumed that one layer of the atoms has by some means had the axes rotated through 90° to be perpendicular to the plane of the paper. Since this layer is acted upon by the Weiss field, H_w, due, we suppose, mainly to the two layers of atoms, one on either side, the work done to produce the condition shown in Fig. 4(*a*) is $H_w M_s v$, where v is the volume of the crystal appropriate to one layer. If, on the other hand, the magnetic axes of the whole of the crystal to the right of a boundary plane had been rotated through 90°, as represented in Fig. 4(*b*), the work done would have been halved because the interaction is across one boundary surface only instead of two. The condition shown in Fig. 4(*b*) might therefore represent a 90° boundary between two domains. If a further rotation of 90° occurred, as in Fig. 4(*c*), to make a 180° boundary, a doubling of the energy would occur, so that in this case the work done would again be $H_w M_s a/2$ per unit area of boundary, where a is the lattice constant of the crystal. However, it has been shown that such a sharp transition as this between two domains would not, in fact, occur. If the twist of 90° or 180° is assumed to take place gradually over a boundary of finite thickness, the boundary energy arising from the interaction between the neighbouring layers of atoms decreases. To a first approximation, at least, the energy per unit area of the boundary surface, if the boundary wall is n layers thick, is $1/n$ of the energy for a sharp transition. This may be likened to the work required to twist the ends of an elastic rod through a given angle, the work done being inversely proportional to the length of the rod. The boundary wall will therefore tend to expand in thickness in order to reduce the interaction energy, but this expansion is arrested by the energy of magnetic anisotropy in the wall, which increases approximately in proportion to the thickness of the wall. The energy of magnetic anisotropy for iron is least for the cube-edge directions. In the boundary wall the atomic magnetic axes are deflected in successive layers away from these directions, as shown in Figs. 4(*d*) and 4(*e*). The mean increase in this energy per unit volume of the boundary wall is approximately $K_1/8$, where K_1 is an experimentally-observable anisotropy constant for the material. The boundary wall will, in fact, expand to a thickness which makes the sum of the interaction and anisotropic energies a minimum. Calculations indicate that the wall thickness for a 180° boundary in iron is about 10^{-5} cm, or about 700 atom layers, with a wall energy of about 1 erg/cm^2.

To return now to Fig. 3(*e*): the components of energy in the iron block which will determine the thickness, d, of the plate-like domains are the energy of the boundary surfaces, say 1 erg/cm^2, and the strain energy, say $\lambda_s^2 E$ per unit volume of the closure domains (where E is Young's modulus for iron). The thickness d may be calculated as the value which makes the sum of these energies a minimum. If L is the length of the block, and L and d are in centimetres, the approximate value for d is $0{\cdot}05\sqrt{L}$. Hence, if L is between 1 cm and 1 mm, d lies between about 0·5 and 0·1 mm. This is in good general agreement with experiperimental observation.

(2.2) Experimental Results

If a ferromagnetic crystal, which may be part of a polycrystalline specimen, is electrolytically polished and then wetted with a soap solution containing particles of iron oxide (Fe_3O_4) in colloidal suspension, particles will be attracted to the domain boundaries by stray magnetic fields. This is a refinement of the technique used in magnetic crack detection. The domains are thus mapped out and the pattern may be viewed by a microscope, for example, with a magnification factor of the order of 300. In iron or silicon-iron, when the crystal surface coincides approximately with a cube-face crystallographic plane, i.e. a (100) plane, simple patterns are observed which confirm Néel's theoretical predictions. In other cases very complicated patterns may be seen, which are not easy to interpret. Ingenious techniques have been devised which enable the directions of the spontaneous magnetization in the domains under observation to be determined.[10–12]

The simplest of the observed domain structures, due to Williams,[10] is shown in Fig. 5(*a*), which is, however, not drawn to scale. The specimen consisted of a closed magnetic circuit cut from a single crystal of 3·8% silicon-iron in the form shown in the Figure, each of the four sides of the specimen being parallel to cube-edge crystallographic directions. The specimen was heated to above the magnetic change point of the material, to eliminate the domain structure. After slow cooling it was found that the entire specimen consisted of four domains, as shown in Fig. 5(*b*), with the four diagonal domain boundaries at the corners. The sum of the four components of energy already mentioned will be least in this case, since both the magnetic anisotropic energy and the total area of the boundaries are a minimum, the magnetostatic energy is zero and the magnetostrictive strain energy will be small. It was found that the demagnetized condition of the specimen was as shown in Fig. 5(*a*), with eight domains. Experimental observation showed that magnetization of the specimen proceeded by an inward or outward movement of the boundaries, causing one set of four domains to grow at the expense of the remaining four. During this process the Barkhausen effect was observed, indicating minute discontinuous jumps in the boundary movement.[12]

Other patterns observed by Williams on single crystals of silicon-iron with the surface parallel to a cube face are shown in Fig. 6. In Fig. 6(*a*) the closure domains predicted by Néel are clearly shown. Fig. 6(*b*) shows another kind of pattern. The arrows indicating the saturation magnetization in the domains

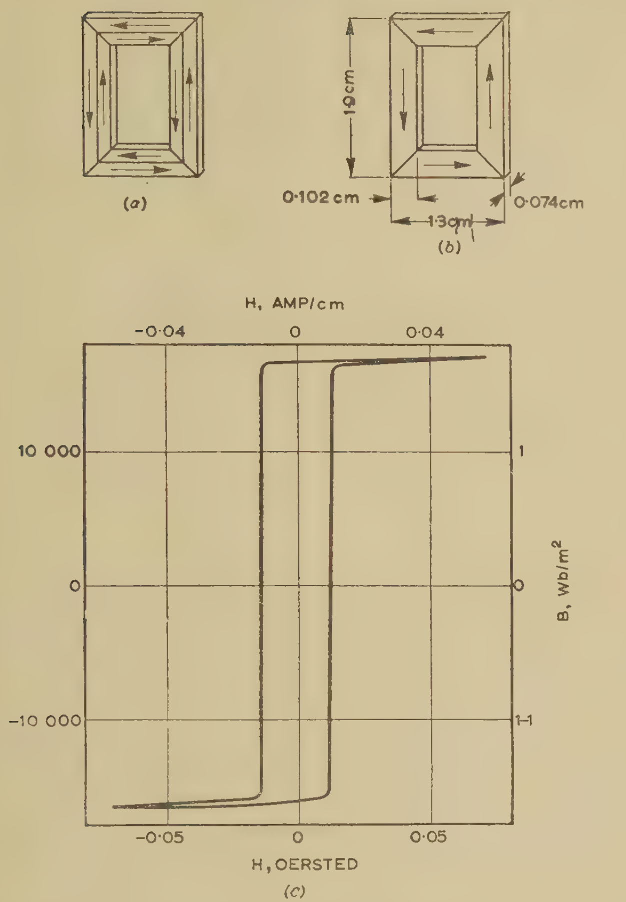

Fig. 5.—Simple domain structure in a single-crystal specimen of 3·8% silicon-iron, together with its hysteresis loop (Williams).

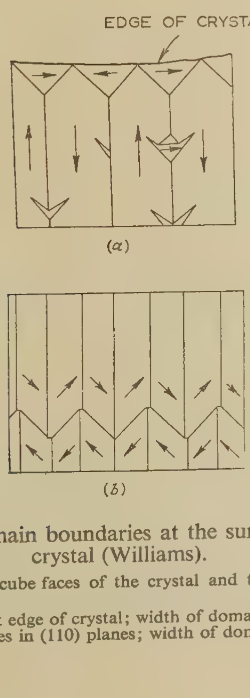

Fig. 6.—Observed domain boundaries at the surface of a silicon-iron crystal (Williams).

Surfaces are parallel to cube faces of the crystal and the arrows are parallel to cube edges in each case.
(a) Closure domains at edge of crystal; width of domains is about 0·14 mm.
(b) Diagonal boundaries in (110) planes; width of domains is about 0·08 mm.

are also parallel to cube-edge crystal directions in both of these diagrams. The principal domain boundaries in Fig. 6(*b*), shown by the vertical lines, are therefore diagonal planes [(110) planes] in the crystal which Néel also predicted would exist in certain circumstances. The application of a magnetic field in the horizontal direction in Fig. 6(*b*) was found to cause the zigzag boundary to move up or down, depending on the direction of the field, in order to increase the resultant magnetization in the field direction, as would be expected.

(2.3) General Theory of Magnetization

In spite of the fact that much is now known about ferromagnetic domain structure, more particularly in iron and silicon-iron, no satisfactory general theory has been developed which enables magnetization curves and hysteresis loops to be calculated in terms of known parameters of the material. Only simple cases have been considered in the preceding Section. When the surface of the crystal is not parallel with a particular crystallographic plane the domain patterns are more intricate. The energetics associated with domain boundary movements during magnetization of a polycrystalline specimen are further complicated by the presence of the boundaries between the constituent crystals and by internal strains and other imperfections in the crystals. A number of suggestions have, however, been made of mechanisms in a ferromagnetic crystal which may impede the movement of domain boundaries in the presence of an applied magnetic field and so govern its permeability and hysteresis.

The general case of a boundary movement is illustrated in Fig. 7. A portion of a single crystal of iron between the broken

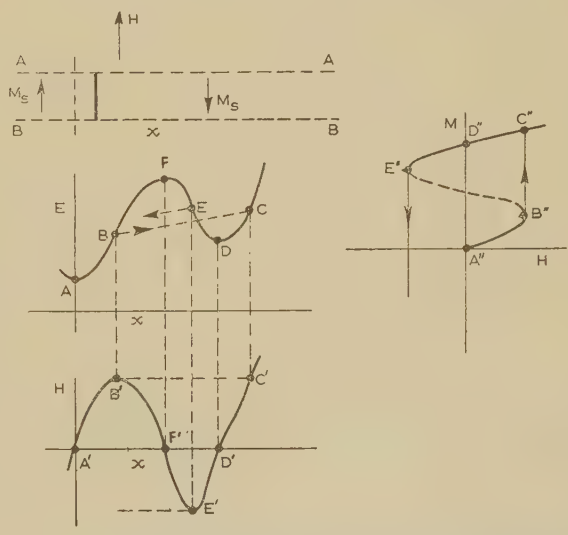

Fig. 7.—General case of a boundary movement with hysteresis.

lines AA and BB with a single 180° boundary is considered. It is supposed that, as the boundary moves a distance x, energy E is stored reversibly in the crystal as shown by the curve AFDC. If the movement is due to the applied field H, then, in fact,

$$H = \frac{1}{2M_s}\frac{dE}{dx}$$

and this field is shown by the curve A′F′D′C′. When H is increased to the point B′ the boundary jumps forward to C′, and if H is now reduced to the negative value at E′ a jump in the reverse direction occurs. The hysteresis loop for this elementary domain boundary is therefore as shown, having the characteristic features

of remanence, coercive force and a Barkhausen discontinuity. The problem is to find the mechanism whereby the energy varies with the boundary position. Becker[13,14] has shown that such a mechanism would be provided by internal stresses in conjunction with the inherent magnetostriction characteristics of the material. Values of initial permeability calculated from this theory are of the right order of magnitude for relatively pure and carefully-treated specimens of iron and nickel-iron.[15,16]

Kersten has suggested that the movement of a domain boundary would be impeded by the presence of impurities in its path.[17] Fig. 8(a) shows a spherical non-ferromagnetic particle, or a

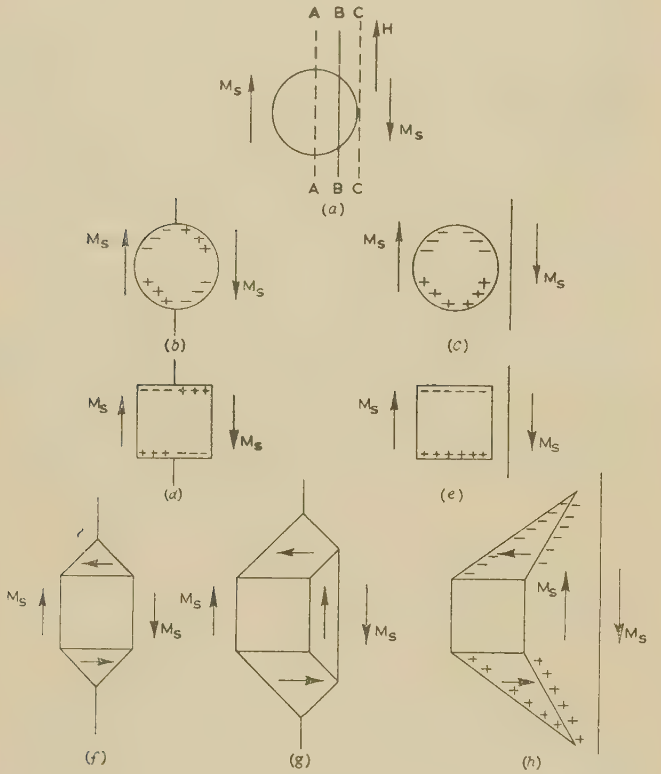

Fig. 8.—Movement of a domain boundary past an inclusion in an iron crystal.

(a) Kersten.
(f), (g), (h) Néel.

cavity, in an iron crystal. If a domain boundary bisects the particle as shown at AA, there is a hole in the boundary surface of maximum size. If the boundary moves to the left or to the right, as at BB, the perforation in the boundary wall becomes smaller. Therefore this movement increases the boundary area and so increases the total energy of the boundary wall. Hence work must be done by an increasing magnetic field to move the boundary from AA to BB and up to the limiting position CC from which the boundary might jump forward with no further increase in the field. This tendency for domain boundaries to cling to inclusions in the metal, so providing a hindering mechanism to their free movement, has been further elaborated by Néel[18] who, however, pointed out a fundamental objection to Kersten's simple idea. Kersten neglected the free poles which would appear at the surface of the particle or cavity. These are represented by the positive and negative signs in Figs. 8(b) and 8(c). With this surface polarization is associated magnetostatic energy as, for example, in the cases shown in Figs. 2, and this is, in general, of a much higher order of magnitude than Kersten's boundary energy. The action of the magnetic fields set up by the free poles would, in fact, be to set up an auxiliary formation of domains around the particle in such a way that the energy was reduced. It is not easy to see what arrangement would occur near a spherical particle, but on the assumption of a rectangular activity aligned with the crystal axes in iron, for example, a simple formation of minimum energy may be expected. The energy associated with the condition shown in Fig. 8(d) is greatly reduced by the formation of a pair of closure domains, as shown in Fig. 8(f). The magnetostatic energy has been eliminated in favour of the relatively small energy of the extra 90° boundaries. The main domain boundary will still tend to cling to the inclusion or cavity. Work must be done to move the boundary, because the total domain boundary areas will grown, as shown in Fig. 8(g). Eventually, when the applied field is sufficient the boundary snaps away from the particle, as shown in Fig. 8(h). Néel predicted—and this was later confirmed experimentally—that auxiliary domains of the spiked shape shown in Fig. 8(h) were to be expected. Since the boundaries of these spikes cannot be quite at 45° to the magnetization vectors, weak free poles at the boundary surfaces must occur, as shown, and hence there is some magnetostatic energy, but the total energy of the condition shown in Fig. 8(h) is less than that of the condition shown in Fig. 8(e). Néel spikes are a common feature of observed domain patterns: they come into being in order to reduce the total energy of the domain assembly to a minimum; examples may be seen in Fig. 6(a).

Néel has suggested that patches of free pole may also occur in the body of a crystal, owing to local variations in chemical composition, the effect of internal strains and other heterogeneities. Variations in magnetostatic energy will occur when a boundary passes over these areas, so providing a restraining mechanism as outlined in general terms in Fig. 7. The number of variables and the complexities of the problem, however, stand in the way of a simple and satisfactory quantitative solution which would enable the useful magnetization characteristics of ferromagnetic materials to be calculated.

(2.4) The Problem of High Coercivity

Permanent-magnet materials in general are characterized by high coercivity, and commercial materials may have coercivities of 600 oersteds (480 amp/cm) or more. The field strength required to reduce the intensity of magnetization to zero after saturation—which is one way of defining coercivity—may also have values for some alloys much greater than this; for example, coercivities of 1 750 and 3 650 oersteds have been reported for iron–platinum and cobalt–platinum alloys, respectively. None of the theories just described, based on restraints on the movement of domain boundaries, is able to account for such high values. Moreover, it has been found that permanent magnets can be made by pressing together fine particles of soft iron. Soft iron may normally have a coercivity of about 1 oersted, but with iron powder having a particle size of about 10^{-5} cm, values of over 400 oersteds may be achieved.[19] A theoretical explanation of this phenomenon has been put forward by Néel[20] and independently by Stoner and Wohlfarth.[21] The theory which they advance is well able to explain also the highest coercivities so far observed in alloys.

Consider first a spherical ferromagnetic particle of diameter d, as shown in Fig. 9. If this is a single domain, as in Fig. 9(a), it will have magnetostatic energy of $\frac{1}{2}N_dM_s^2$ per unit volume, where $N_d = \mu_0/3$ is the demagnetizing factor of the sphere. This energy, which is independent of the diameter, could be made to vanish if the sphere were demagnetized. This might be done by taking the parallel planes of atoms and rotating each by equal increments of angle so that a total rotation of 360° was achieved from top to bottom of the sphere, as shown in Fig. 9(b).

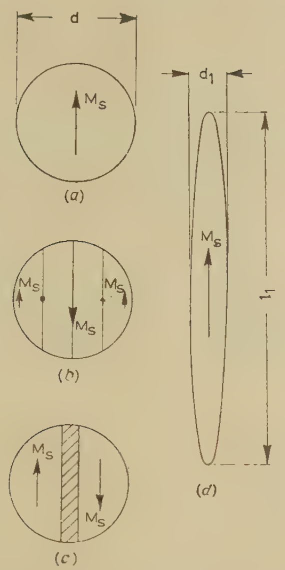

Fig. 9.—Ferromagnetic particles which are single domains.
(a) Spherical particle; this is a single domain if $d < 1 \cdot 5 \times 10^{-6}$ cm.
(b) Demagnetized particle has greater energy than (a) when d is below critical size.
(c) Boundary between domains has greater energy than (b).
(d) Prolate spheroid; if, for example, $l_1/d_1 = 10$ this is a single domain when $d_1 < 6 \times 10^{-6}$ cm (Stoner and Wohlfarth).

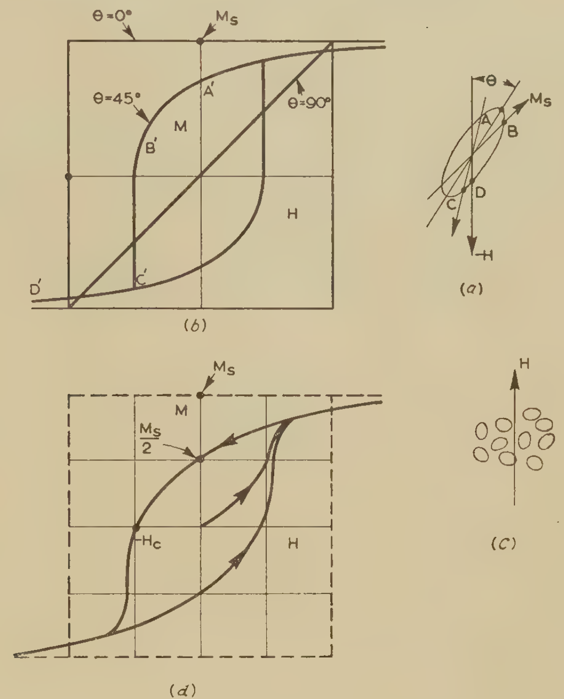

Fig. 10.—Hysteresis loops of single-domain particles in the form of prolate spheroids (Stoner and Wohlfarth).
(a), (b) Single particle inclined to the magnetic field.
(c), (d) Material composed of particles randomly oriented.

Work would have to be done against the Weiss molecular field or forces of interaction, as in the case of a domain boundary wall. This interaction energy per unit volume may be calculated in terms of M_s, the Weiss field, the lattice constant and the diameter of the particle. It increases inversely as d^2, and hence when d is below a certain critical value the condition shown in Fig. 9(b) is of higher energy than that shown in Fig. 9(a), and the particle will therefore remain a single domain. Moreover, if a domain boundary were introduced, as shown in Fig. 9(c), to split a particle into two domains this narrow boundary would, in general, have more energy than the sphere in the condition shown in Fig. 9(b). Stoner and Wohlfarth calculate that for iron the critical value of d is about $1 \cdot 5 \times 10^{-6}$ cm. Spherical particles smaller than this must be single domains. However, if the particles are not spherical they may be larger and still remain as single domains; for example, a prolate spheroid as shown in Fig. 9(d) of polar length 60×10^{-6} cm and an equatorial diameter of 6×10^{-6} cm would still be a single domain. These sizes, it may be noted, are of the same order as those of the powder-magnet particles.

Stoner and Wohlfarth's theory of coercivity now depends upon the behaviour in a magnetic field of the magnetization vector in a single-domain particle which is not, in fact, spherical. Such a particle in the form of a prolate spheroid is shown in Fig. 10(a). The demagnetization factor of this particle is least in the direction of the polar axis and greatest in the equatorial direction. The magnetostatic energy is therefore least when M_s lies along the polar axis, and work must be done to rotate the vector away from this direction. If the particle is inclined to the direction of an applied field at an angle θ, as shown in Fig. 10(a), there is an associated hysteresis loop depending on the value of θ, as shown in Fig. 10(b). When $H = 0$, M_s is at A, giving the remanent point A′, where $M = M_s \cos \theta$ in the field direction. As H increases in the negative or downward direction M_s moves to B, giving a point B′ on the hysteresis loop. Eventually M_s reaches a position of instability and jumps round to position C, giving also the point C′. When H becomes great enough M_s comes into line with H at D, giving the saturation value at D′. Calculated hysteresis loops for different values of θ are shown in Fig. 10(b). The theory shows that when $\theta = 0$ the coercivity of the particle is given simply by $H_c = M_s(N_b - N_a)$, where N_a and N_b are the demagnetization factors in the polar and equatorial directions respectively. If the material is made up entirely of single-domain particles all of the same shape but orientated at random, as shown in Fig. 10(c), the mean calculated loop is as shown in Fig. 10(d). The coercivity is then given by $H_c = 0 \cdot 479 M_s(N_b - N_a)$ and the remanence is one-half of the saturation intensity of magnetization. With a knowledge of the shape of the particles, the coercivity may be calculated. The observed value of coercivity, say 400 oersteds, obtained in iron-powder magnets is accounted for if the ratio of equatorial diameter to length is about 0·9, representing a comparatively small deformation from the spherical shape. If, on the other hand, the particles were greatly elongated, a theoretical value of about 5 000 oersteds would be obtained for randomly orientated particles, and this would be increased to about 10 000 oersteds in one direction if the particles were aligned parallel with one another.

This theory, which so aptly applies to powder magnets, may also account for high coercivity in alloys. For example, a good deal of work has been done on the permanent-magnet material Alni. When appropriately heat-treated this material consists of an iron phase in an arrested state of precipitation in a second phase or matrix of FeNiAl. The latter phase has a saturation value only about one-third of that of iron. The coercivity of this alloy, about 500 oersteds, might therefore be explained on the supposition that the iron precipitates are below the critical size and are therefore single domains.

(3) THE FERRITES

(3.1) Crystal Structure

The iron oxide Fe_3O_4 occurs in nature as the mineral magnetite which was the lodestone of the ancients. It has in its

natural form an initial relative permeability of the order of 10 at room temperature and a coercivity of about 20 oersteds. When artificially produced in pure form the initial permeability may be raised to about 70. Snoek[22,23] carried out a systematic investigation of oxides of the same structure as magnetite, and by substituting other elements such as manganese, nickel or zinc for some of the iron atoms he created a new series of magnetic materials much superior to magnetite which are now called ferrites. Compared with the metals these materials have extraordinarily high electrical resistivities, which enables them to be used at the highest frequencies without the obscuring effects of eddy currents. They are hard, ceramic, crystalline substances.

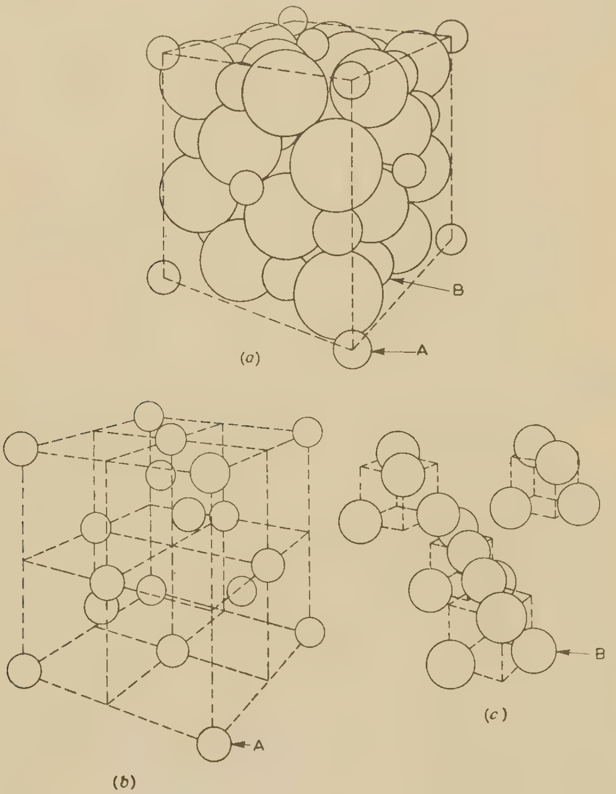

Fig. 11.—Inverse spinel crystal structure of the magnetic ferrites.

(*a*) Volume inside the cube corresponds to eight molecules. The largest spheres are negative oxygen ions (O^{2-}) on a face-centred cubic lattice.

(*b*) Interstitial positive trivalent iron ions (Fe^{3+}) abstracted from the structure shown at (*a*). These are on A-sites.

(*c*) Interstitial positive metal ions, also abstracted from (*a*), on B-sites. Half of these are positive trivalent iron ions (Fe^{3+}): the other half are positive divalent ions which may be, for example, Mn^{2+}, Fe^{2+}, Co^{2+} or Ni^{2+}.

Fe_3O_4 may be called an iron ferrite. It exists as ionic cubic crystals with the structure shown in Fig. 11(*a*). We may write

$$Fe_3O_4 = Fe^{3+}(Fe^{2+}Fe^{3+})O_4^{2-} \quad . \quad . \quad . \quad . \quad (1)$$

The symbol O^{2-} represents an oxygen anion or an oxygen atom to which two electrons have been added, giving it a resultant negative charge of two units. Fe^{2+} represents an iron atom which has given up two electrons and is therefore left with a resultant positive charge of two units. Similarly Fe^{3+} is a cation with three units of positive charge. The volume inside the cube shown by the broken lines in Fig. 11(*a*) corresponds with that of eight molecules of Fe_3O_4. Ions whose centres are outside the cube have been omitted. The ions are shown in approximately their correct relative sizes. The negative oxygen ions pack closely together on a face-centred cubic system, as shown by the largest spheres. The smaller positive iron ions, in the completely ordered crystal, also occupy regular cubic positions, but in the interstitial spaces between the oxygen ions. There are two sorts of available space in the oxygen lattice, one smaller than the other. The smaller spaces are occupied by the iron ions marked A in Fig. 11(*a*). These have been abstracted in Fig. 11(*b*), and will be said to occupy A sites. The ions in these positions are represented by Fe^{3+} outside the brackets in eqn. (1). The ions occupying the larger B sites have been abstracted in Fig. 11(*c*). These correspond to ($Fe^{2+}Fe^{3+}$) in eqn. (1). Thus half the ions in B sites are divalent and half are trivalent. There are, in fact, in the volume corresponding to eight molecules, eight Fe^{3+} ions in A sites, with eight Fe^{3+} and eight Fe^{2+} ions in B sites. A second difference between A and B sites is shown in Fig. 12. The A ions have four near-neighbour oxygen ions

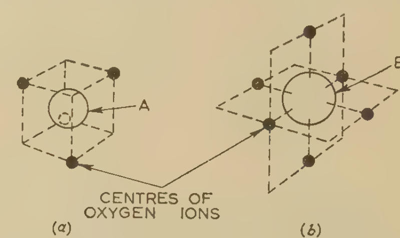

Fig. 12.—Two types of interstitial site in the oxygen-ion lattice.

● ● Centres of the oxygen ions.

(*a*) A is an Fe^{3+} ion in an A-site with four near-neighbour oxygen ions in a magnetic ferrite.

(*b*) B is a trivalent iron ion or a divalent metal ion in a B-site with six near-neighbour oxygen ions.

in tetrahedral positions, while the B ions have six near oxygen neighbours in octahedral positions as shown. These differences in the two sites are important in explaining the observed values of magnetic saturation in the ferrites.

The disposition of the positive ions described above for Fe_3O_4 corresponds to an inverse spinel structure, and to this class all the magnetic ferrites belong. In manganese ferrite, for example, divalent manganese, Mn^{2+}, takes the place of Fe^{2+} in the B sites; and similarly for other elements such as cobalt and nickel.

On the other hand, in the zinc or cadmium ferrites the structure is that of a normal spinel: both the trivalent iron ions are in B sites and the divalent zinc or cadmium is in A sites, giving $Zn^{2+}(Fe^{3+}Fe^{3+})O_4^{2-}$. Taken alone, these ferrites are not magnetic.

(3.2) Ferrimagnetism

The magnetic saturation value of the ferrites is low when compared with metallic iron; for example, Fe_3O_4 saturates at about 6000 gauss, whereas if all the iron ions were making their maximum contribution this value would be raised to about 21000 gauss, which is, in fact, approximately that of iron itself. Néel[24] has advanced a theory which accounts for the observed saturation values of the ferrites.

Both the chemical bonding between atoms and their magnetic moments are associated with the outermost electrons in their electronic structure. Fig. 13 shows the first four main shells and their sub-shells around the central atomic nucleus which provide places for the electrons to occupy. These places are filled from the centre outwards as the periodic table of the elements is built up. In general, as previously stated, the electrons with positive and negative spins pair off and so produce no resultant magnetic moment. Any shell which is completely full has, in fact, no magnetic moment. In the metallic atoms with which we are here concerned, except zinc, the 3d sub-shells shown in Figs. 13 and 14 are not full and the pairing-off is not complete. Thus referring to the 3d shells in Fig. 14, the free,

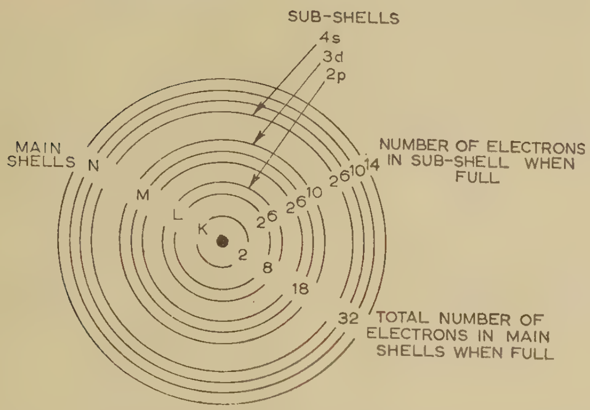

Fig. 13.—The first four main shells and the corresponding sub-shells (three of which are labelled) in an atom; the total numbers of orbital electrons required to fill these shells are given.

un-ionized atoms of manganese, iron, nickel and zinc will be seen to have magnetic moments of 5, 4, 2 and $0\mu_B$ respectively. It will also be seen in Fig. 14 that the free atom of oxygen has six electrons in its outermost shell (the L shell), which is two short of the eight required to fill it. In the chemical bonding which occurs, for example, in Fe_3O_4 the four oxygen atoms in the molecule each take two electrons from the iron atoms. The oxygen-ion L shells are then full and contribute no magnetic moment. One iron atom gives up the two loosely held electrons in the 4s sub-shell and the other two iron atoms give up these and also one each from the 3d sub-shells. Therefore a total of eight electrons is transferred from the iron to the oxygen and the two kinds of iron ion shown in Fig. 14 occur in Fe_3O_4. One of these clearly has a moment of $4\mu_B$ and the other $5\mu_B$. In other ferrites with the inverse structure another divalent ion, e.g. Mn^{2+}, is substituted for the divalent iron ion Fe^{2+}.

The carriers of the magnetic moment in the ferrites are therefore the uncompensated spinning electrons in the metal ions. The oxygen ions have zero moments. Between the spinning electrons in the neighbouring metal ions strong quantum mechanical forces of interaction occur, as mentioned in the Introduction for the ferromagnetic metals. However, according to Néel this interaction is negative in the ferrites. This means that the forces act to hold the neighbouring atomic magnetic axes anti-parallel or opposite in direction. In ferromagnetism the interaction is positive, and parallel alignment of the axes occurs. In the ferrites three sets of forces will exist—those between ions on A sites, those between ions on B sites and those between the A and B ions. These interactions may be referred to as A–A, B–B and A–B. It is considered that the A–A and B–B interactions are relatively weak and that therefore the A–B negative interaction predominates. The result is that at low temperatures the magnetic axes of the ions on A sites are held anti-parallel with those of the B sites, i.e. the A and B axes point in opposite directions. The Table summarizes the conditions.

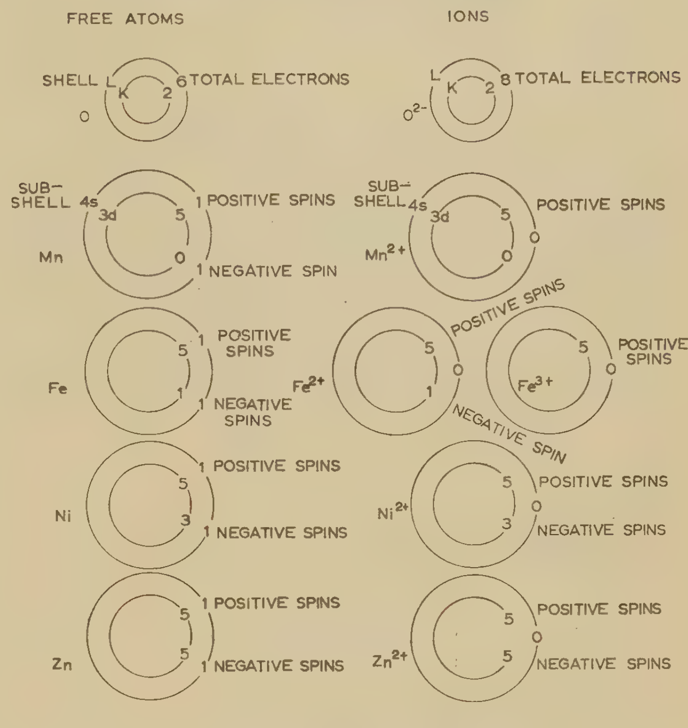

Fig. 14.—The outer electrons which are responsible for the chemical and magnetic properties.

On the left are the un-ionized atoms and on the right the ionized atoms in the state in which they occur in the ferrites.

The excess of electrons with positive spin over those with negative spin determines the magnetic moment of the atom or ion.

Thus in manganese ferrite the total moment per molecule pointing south is $5\mu_B$ and the total pointing north is $(5 + 5)\mu_B$, giving a result of $5\mu_B$. The same argument applies to the other ferrites of inverse structure. Zinc ferrite, on the other hand, has the normal structure. The zinc ions on A sites have no magnetic moment: there are therefore no A–A or A–B interactions. On the B sites, however, there are iron ions each with a moment of $5\mu_B$, but since the B–B interaction is negative and there is now no overriding A–B interaction, anti-parallelism occurs in the B sites and the resultant magnetic moment is zero. This condition of equal and opposite sets of magnetic ions is called anti-ferromagnetism, and it occurs in many chemical compounds as well as in the normal ferrites. When the opposing arrays of magnetic moments are unequal the material is said to be "ferrimagnetic." In both cases the materials will have a domain structure. In the final column of the Table are observed moments due to Gorter,[25] which are seen to agree well with Néel's prediction.

The various ferrites may be combined together, since they form solid solutions with each other. The best magnetic properties for practical use are found in some of these mixed

Ferrite	Structure	Ion site, magnetic moment and direction of magnetic axis											Resultant magnetic moment per molecule, μ_B	
		A site			B site									
		Ion	μ_B	Direction	Ion	μ_B	Direction	Ion	μ_B	Direction	4 ions	μ_B	Calculated	Observed
Manganese	Inverse	Fe^{3+}	5	↓	Mn^{2+}	5	↑	Fe^{3+}	5	↑	O_4^{2-}	0	5	5·0
Iron	Inverse	Fe^{3+}	5	↓	Fe^{2+}	4	↑	Fe^{3+}	5	↑	O_4^{2-}	0	4	4·2
Nickel	Inverse	Fe^{3+}	5	↓	Ni^{2+}	2	↑	Fe^{3+}	5	↑	O_4^{2-}	0	2	2·3
Zinc	Normal	Zn^{2+}	0		Fe^{3+}	5	↑	Fe^{3+}	5	↓	O_4^{2-}	0	0	0

ferrites, particularly in manganese–zinc and nickel–zinc ferrites. Particulars of the commercial materials are to be found elsewhere.[26]

(4) MAGNETIC PHENOMENA AT HIGH FREQUENCIES

(4.1) Variation of Magnetic Properties with Frequency

If measurements of the magnetic properties of a ferrite are made over a complete frequency range from zero to the microwave region, abnormal conditions of permeability and loss are encountered in parts of the spectrum, which are reminiscent of the resonances which may arise in a mechanical system subject to forced vibrations of increasing frequency. The observations are most conveniently expressed by considering the magnetic permeability as a complex quantity and plotting the coefficients μ' and μ'' of its real and imaginary parts. Fig. 15 shows one

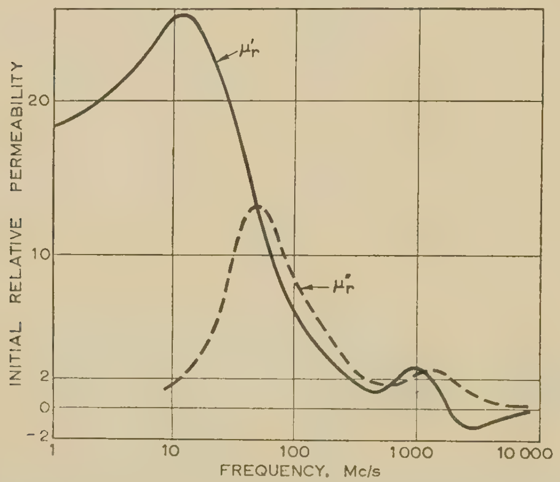

Fig. 15.—Real and imaginary parts of complex initial permeability of a ferrite in relation to frequency, showing resonances at approximately 50 and 1 200 Mc/s (Rado).

result obtained by Rado[27] for a ferrite at room temperature in which resonant effects are occurring in the region of 50 Mc/s and again at about 1 200 Mc/s.

The meaning of real and imaginary permeability may be explained by means of the vector diagrams in Fig. 16. If a specimen of magnetic material is magnetized by means of a sinusoidal alternating magnetic field represented by H in Fig. 16(a), and if there are losses in the material, the flux density

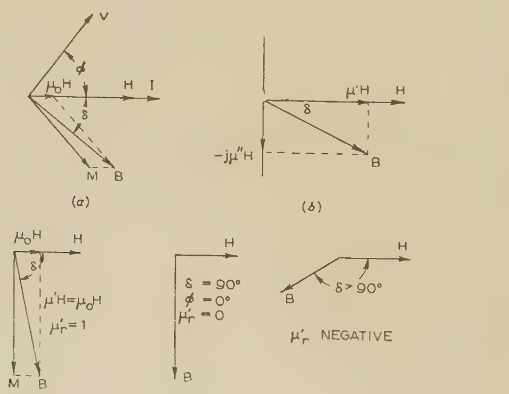

Fig. 16.—Real and imaginary parts of complex permeability.

As the angle of lag of the flux density increases, the real component of the relative permeability may fall through the values unity and zero and become negative.

B, also assumed to be sinusoidal, will lag H in phase position by a loss angle δ. If the specimen is magnetized, for example, by a winding carrying a current I and with a voltage V applied, H and I are in phase and V leads B by 90°. The power factor of the material is therefore $\cos\phi = \sin\delta$, and this is zero when B and H are in phase and increases as δ increases. Since B is the vector sum of $\mu_0 H$ and the intensity of magnetization M (in M.K.S. units: or alternatively the vector sum of H and $4\pi M$ in C.G.S. units), M will have the magnitude and phase position shown in Fig. 16(a). When B and H are plotted as complex quantities on an Argand diagram, as in Fig. 16(b), with real quantities plotted as abscissae and imaginary quantities as ordinates, B consists of the two components $\mu' H$ in phase with H and $-j\mu'' H$ in quadrature with it; whence $B = (\mu' - j\mu'')H = \boldsymbol{\mu} H$ where $\boldsymbol{\mu}$ is the complex permeability, so that $\boldsymbol{\mu} = \mu' - j\mu''$ and $\tan\delta = \mu''/\mu'$. The quantity μ' determines the component of flux which is in phase with H and with which no loss is associated. The quantity μ'' relates to the flux component in quadrature with H and determines the losses.

The curves in Fig. 15 for μ'_r and μ''_r, i.e. the relative permeabilities, show that the real component may pass through unity and zero and, indeed, may become negative. Figs. 16(c) and 16(b) show how, in fact, these conditions may be represented on vector diagrams. In Fig. 16(c) the intensity of magnetization has fallen 90° behind H in phase position. In this case δ is a little less than 90°, and clearly the only component of B in phase with H is $\mu_0 H$. Therefore in this case $\mu' H = \mu_0 H$ or $\mu' = \mu_0$ or $\mu'_r = \mu'/\mu_0 = 1$. In Fig. 16(d) B has fallen further back, so that $\delta = 90°$. In this case B consists entirely of the component $\mu'' H$ and then μ' and $\mu'_r = 0$. In Fig. 16(e) B is lagging H by more than 90°. In this case the real component of B is negative, so that μ'_r is negative.

(4.2) Domain Boundary Resonance

It is instructive to consider first the simple case of mechanical resonance shown in Fig. 17(a). The mass m is acted upon by a sinusoidally-varying applied force $P \sin\omega t$ against the restoring force of the springs kx and the damping forces $k_1 dx/dt$, assumed to be proportional to the velocity of motion of the mass. The differential equation is

$$m\frac{d^2x}{dt^2} + k_1\frac{dx}{dt} + kx = P\sin\omega t$$

and the steady-state solution of this gives a relation with which engineers are familiar between displacement, x, and time, t, for any given angular frequency, ω, of the applied force. If ω is raised from zero upwards and there is no damping, i.e. $k_1 = 0$, the alternating displacement of the mass remains in phase with the applied force, there are no losses and the amplitude of the oscillation increases with increasing frequency until, when $\omega = \omega_1 = \sqrt{(k/m)}$, the amplitude theoretically becomes infinite. When ω passes this resonant point the amplitude falls again, approaching zero at high frequency. On the other hand, if light damping is present the displacement lags behind the applied force by an increasing phase angle, which becomes 90° at resonance and exceeds 90° when $\omega > \omega_1$.

In the comparison of this mechanical case with the magnetic case the applied mechanical force is related to an applied magnetic field and the displacement of the mass with intensity of magnetization. In Fig. 17(b) is shown a 90° domain boundary of unit area in the presence of an applied magnetic field. The boundary wall is of finite thickness, as already described, with a twist of the atomic magnetic axes across the boundary, as shown, for example, for another type of 90° boundary in Fig. 4(d). As the boundary wall moves to give the displacement x in

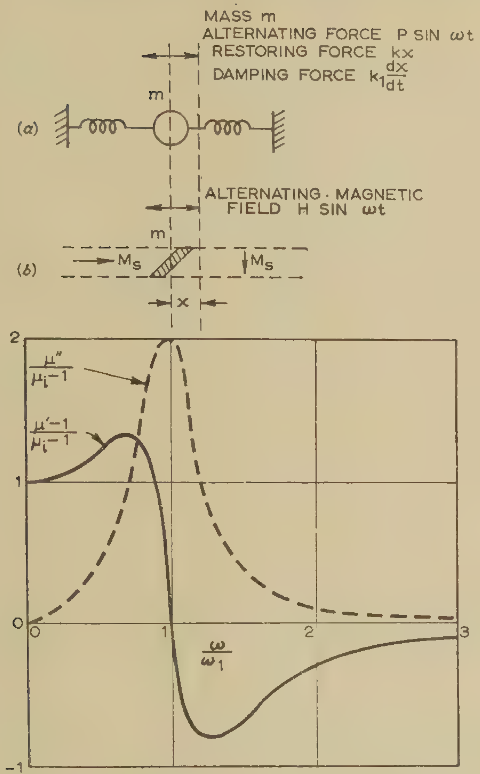

Fig. 17.—Forced oscillation of a mass in a damping medium at (*a*) compared with domain-boundary oscillations in an alternating magnetic field at (*b*).

The curves give calculated values of the real and imaginary components of the permeability in terms of the initial permeability at zero frequency for one value of damping.

Fig. 17(*b*) a rearrangement of spinning electrons in the volume swept out must occur, and so the boundary must possess inertia which may again be represented by a mass m. Without being able to specify the loss mechanism it will again be assumed that the damping force is proportional to velocity. The way in which restoring forces on the boundary may arise has already been discussed in Section 2.3. In Becker's theory of initial permeability, for example, the stiffness constant k would, for small displacements, be a simple function of the magnetostriction and the mechanical stress gradient in the material in the region of the boundary. The force acting on the boundary is now $HM_s \sin \omega t$, so that HM_s replaces P. If it is assumed that magnetization occurs entirely by oscillations of boundaries according to this model, it is easily shown that

$$\frac{\mu' - 1}{\mu_i - 1} = \frac{1 - a^2}{(1 - a^2)^2 + b^2 a^2} \text{ and } \frac{\mu''}{\mu_i - 1} = \frac{ba}{(1 - a^2)^2 + b^2 a^2}$$

where μ_i is the permeability at zero frequency, $a = \omega/\omega_1$ and $b = k_1/m\omega_1$. The curves in Fig. 17 show the calculated values when $b = 0 \cdot 5$. The maximum and minimum values of these curves are increased if b is reduced, i.e. if the damping is less, and vice versa. It is believed that domain-wall resonance effects of this kind are responsible for the observed resonances at the lower frequencies in the ferrites, i.e. at about 50 Mc/s in Fig. 15. Comparison of Figs. 15 and 17, however, indicates that there must also be other complicating factors. One of these, no doubt, is the existence of Barkhausen discontinuities which are ignored in the simple calculations. It may, however, be inferred that at still higher frequencies, where μ_r' falls to relatively low values, domain-boundary movements, either smooth or by Barkhausen jumps, become of diminishing importance. The resonances occurring in the microwave region are, indeed, explained in another way.

(4.3) Gyromagnetic Resonance

The magnetic phenomena represented by the curves in Fig. 15 in the region of 500 Mc/s upwards may be accounted for in terms of gyromagnetic effects associated with the spinning electrons which, as already mentioned, are the elementary magnets in the material. The picture is clearest if we revert to classical, rather than quantum, concepts and thus allow the spin axes to take any position in an applied field.[28–31]

The spinning electron has a magnetic moment of $1\mu_B$ which is the same as that of the smallest orbit in the Bohr atom. If this orbit is represented in Fig. 18(*a*) the relative directions of

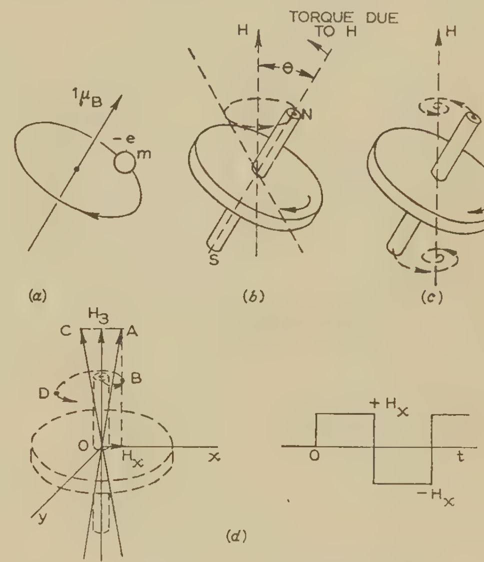

Fig. 18.—Precession of a spinning electron.

(*a*) Electron in smallest Bohr orbit.
(*b*) Spinning electron represented by a spinning top, the stalk of which is a permanent magnet of moment $1\mu_B$. The spin axis will precess about the direction of an applied steady field H.
(*c*) The spin axis will pull into line with H if losses are present.
(*d*) Showing how the angle θ will increase when an alternating field H_x is applied at right angles to the steady field H_z, producing alternating components of magnetization in both the x- and y-directions.

rotation and of the magnetic moment are as shown (remembering that the electron carries a negative charge). However, the angular momentum of the spinning electron is known to be only one-half of that for the orbit. It is therefore as though the spinning electron had its mass distributed as on a disc but with the charge at the periphery. The spinning electron will therefore be represented as the spinning top shown in Fig. 18(*b*), the stalk of which is a permanent magnet of moment $1\mu_B$. If now a steady magnetic field H is applied at an angle θ to the spin axis, an inward torque $H\mu_B \sin \theta$ acts on the magnet in the plane of H and the spin axis and the magnet in the field acquires potential energy $-H\mu_B \cos \theta$. However, in accordance with the properties of the gyroscope, such a torque does not, in fact, alter the angle θ but causes the spin axis to precess around the direction of H on a cone of semi-vertical angle θ as shown. The angular velocity of the precessional rotation is, in C.G.S. units, $\omega_p = \gamma H$ where the magneto-mechanical ratio for spin is $\gamma = e/mc$ and $\gamma/2\pi = 2 \cdot 80$ Mc/s/oersted. The precessional velocity is therefore independent of θ but proportional to H. If there were no losses or other disturbances, then in Fig. 18(*b*) the axis of the elemental magnet would never be pulled into line with H but would con-

tinue precessing at constant velocity with a fixed angle θ, and with no change in the potential energy. If, however, the precessional motion encounters a damping torque, the spin axis is now caused, by the same gyroscopic action which produces precession, to rotate inwards to reduce θ. There is now a loss communicated as heat, by some mechanism which is not clear, to the surrounding material, this loss being equal to the reduction in potential energy of μ_B in the field H. The effect of the losses is therefore to cause the precessional angle θ to fall towards zero, so that eventually the spin axis and H are in line. This is shown in Fig. 18(*c*).

Consider now the spinning electron shown in Fig. 18(*d*), having its axis initially in line with the applied steady field. Suppose at time $t = 0$ a component of field H_x small compared with H_z is applied, so that the resultant field now lies along the direction OA. The spin axis now precesses on a cone about OA with a velocity $\omega_p = \gamma H_z$ approximately. If, when the spin axis has reached the position OB in the xz plane, H_x is reversed the gyroscopic magnet will now precess about the axis OC, and so on. Thus the application of an alternating component H_x in synchronism with the precessional rotation produces a condition of resonance in which components of magnetization in the x- and y-directions would increase. In practice, a sinusoidal field would be applied in the x-direction which modifies the motion just described, and the amplitudes of the magnetization in the x- and y-directions would also be severely damped by losses. Kittel has shown that the resonance frequency depends on the shape of the specimen, since demagnetizing components of magnetic field associated with the components of magnetization in the x-, y- and z-directions must also be taken into account. However, for a spherical specimen the resonant frequency is still given by $\omega_1 = \gamma H_z$, while for a flat plate lying in the xz-plane $\omega_1 = \gamma\sqrt{(B_z H_z)}$ (C.G.S. units) for an applied alternating field H_x. Let numerical values be inserted; then if $H_z = 500$ oersteds the resonant frequency $f_1 = \omega_1/2\pi$ is 1 400 Mc/s for a sphere and about 9 000 Mc/s for a flat plate if the latter is, hypothetically, of iron.

When the frequency of the applied field H_x is much less or much greater than f_1, Kittel has shown that for the x-direction and no losses

$$\frac{\mu' - 1}{\mu_i - 1} = \frac{1}{1 - a^2}$$

where $a = \omega/\omega_1$ which happens to be the same expression as that obtained in Section 4.2 for simple mechanical or domain-boundary oscillations if losses are neglected. This leads to negative values of the real components of permeability when the frequency of the applied field is greater than the resonant frequency.

If in the foregoing the frequency of the applied field had been held constant, a condition of resonance could be achieved by adjusting the steady field H_z to a suitable value. Fig. 19 shows the observed values of μ_r' and μ_r'' for a thin nickel film[32] obtained at a fixed frequency of 24 400 Mc/s with a varying value of H_z.

In the foregoing H_z has been assumed to be an externally-applied steady field. However, gyromagnetic resonance may also occur with internal fields only. Any internal effect which causes the magnetization in a domain to point in a particular direction in the material fixes an axis about which precession may occur. The crystalline forces, already referred to, which produce crystal anisotropy represent such an equivalent magnetic field. The results given in Fig. 15 were, in fact, obtained with no applied steady field. In this connection it should be noted that the Weiss molecular field is to be disregarded, since it acts only to hold neighbouring atomic magnetic axes parallel with one another in any domain, and these axes will precess together.

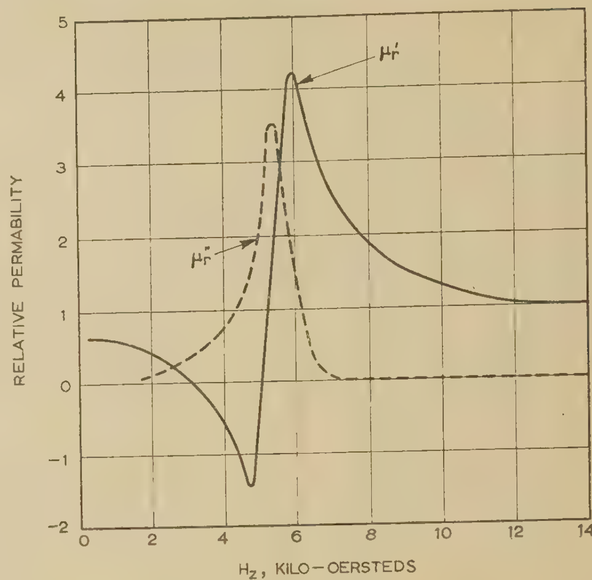

Fig. 19.—Real and imaginary components of relative permeability of a thin film of nickel with a fixed frequency of 24 400 Mc/s and with different values of the steady magnetic field (Standley).

If electromagnetic radiation in the form of a polarized beam of light is passed through a transparent material in the direction of an applied steady magnetic field, the axis of polarization rotates about the direction of propagation of the light. The angle of rotation is proportional to distance of travel, and its direction depends on the direction of the field. The effect is non-reciprocal, in that if the beam is reflected along its original path the rotation continues to increase in the same direction. This is the Faraday effect. The same action occurs with electromagnetic radiations outside the optical range, provided that the losses in transmission are small, i.e. that the medium has the necessary transparency. In the ferrites these conditions may be met at frequencies in the region of 10 000 Mc/s where, as may be seen in Fig. 15, μ'' is small. The mathematical theory of the effect has been developed by Polder,[33] Hogan[34] and others on the basis of the classical model of precessing gyroscopic electrons. A physical picture of Faraday rotation is not easy. Hogan, however, found that in a field of 1 000 oersteds, for example, rotations of the order of 60° per centimetre of travel were obtainable in ferrites. This phenomenon and others associated with it are finding important practical applications in microwave techniques.

(5) CONCLUSION

In the development of the subject of ferromagnetism, theory and experiment have gone hand in hand. In some notable cases the theoretical predictions have come first and the experimental confirmation has followed, as in the case of domain patterns; in many other cases the reverse is true. The subject continues to be an exciting and rewarding one. The invention of those new materials, the ferrites, has greatly aided the advancement of fundamental knowledge of magnetic processes and resulted in remarkable new practical applications, particularly in the microwave region. It seems certain that new materials and new applications are still to come, and, it may be hoped, simplifications also in the theory of the basic interactions on the atomic scale which result in the various forms of magnetism. It is most intriguing to find how the new magnetic phenomena require and confirm the gyroscopic electron, with its electrical, magnetic and mechanical properties, as the elementary unit in magnetism.

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Paper No. 1945 M
Feb. 1956

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A VOLTAGE DIVIDER CONTAINING A NON-LINEAR UNIT

By L. L. ALSTON, Ph.D., B.Sc.(Eng.), Associate Member.

(*The paper was first received* 1st *December*, 1954, *in revised form* 31*st March and* 27*th June, and in final form* 5*th September*, 1955.)

SUMMARY

A voltage divider incorporating a non-ohmic resistor in its low-voltage arm, has been developed for measuring the burning voltage of an arc initiated by a high-voltage flashover. An analysis of the performance of the divider is given, and is supported by proving tests. A design procedure is outlined.

(1) INTRODUCTION

A voltage divider containing a non-linear unit has been developed for applications such as the measurement of a relatively low arc voltage, whilst providing protection of the measuring apparatus against high over-voltages used to initiate the arc by sparkover between electrodes.

Two possible methods for achieving this characteristic were considered and rejected. First, an amplifier could be connected between the low-voltage arm of a conventional divider and the measuring equipment, the output voltage of the amplifier being limited to a safe value determined by the h.t. voltage. In addition to screening problems, the initial saturation of the amplifier introduces serious distortion in the output waveform. Secondly, a gas diode could be connected across the low-voltage arm of the divider, which would then be short-circuited at all voltages in excess of the striking voltage of the diode. This is a technique familiar to high-voltage engineers, but requires a knowledge of the voltage/time characteristic for ionization or deionization of the diode for given waveforms.

The method adopted is shown in Fig. 1. R_H and R_L constitute a conventional resistance divider, having stray capacitances C_H and C_L. R_M is a silicon-carbide non-ohmic resistor,[1] the resistance of which decreases instantly when the voltage across it rises. During the preparation of the paper, the author found that a similar divider had been used by Higham and Meek,[3] but a critical analysis of its performance was not given.

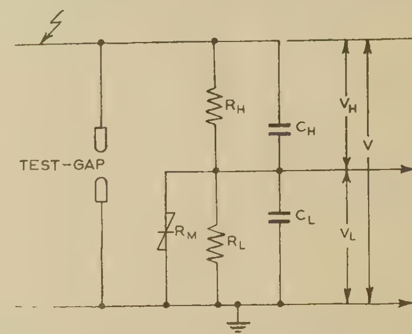

Fig. 1.—The voltage divider, shown connected across a test-gap.

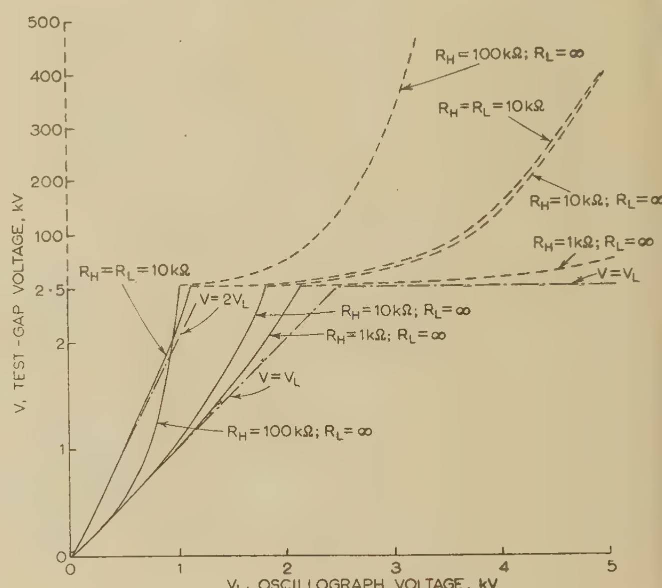

Fig. 2.—Relation between the voltage V at the test-gap (and across the divider) and the voltage V_L at the oscillograph (and across the l.v. arm of the divider), calculated by taking $R_M = 8 \times 10^{16} V_L^{-4}\,\Omega$ and ignoring the stray capacitances associated with the divider.

The V scale is discontinuous at 2·5 kV in order to illustrate both the protective and measuring ranges of the divider.
The straight lines $V = V_L$ and $V = 2V_L$ show the relation between V and V_L for the different values of R_H and R_L, in the absence of R_M.

(2) THEORETICAL CONSIDERATIONS

If we ignore, for the moment, the stray capacitances, the relation between V and V_L for the divider of Fig. 1 is given by

$$V_L = \frac{V}{1 + \frac{R_H}{R_L} + \frac{R_H}{R_M}} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

When V is large, R_M must be much smaller than R_H in order to limit V_L to a safe value. When V has a relatively low value, R_M should be much greater than R_H in order that V_L be substantially independent of R_M over the measuring range. These conflicting requirements can be satisfied because of the non-linear characteristic of R_M, and the corresponding ratios $R_H : R_M$. It will be noted that for a given value of R_M, a high value of R_H improves protection, but a low value of R_H decreases the effect of R_M in the measuring range. This is illustrated in Fig. 2, which shows characteristics of dividers having different values of R_H and R_L.

Ignoring R_M, the divider ratio is $n_\infty = \frac{R_H + R_L}{R_L}$. The effect of R_M is to introduce a percentage error

$$v' = \frac{100}{1 + R_M\left(\frac{1}{R_H} + \frac{1}{R_L}\right)}\,\% \quad . \quad . \quad . \quad . \quad (2)$$

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
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in the measurement of V. Even if allowance has to be made for this, R_M need not be known to a high degree of accuracy, since $R_M \gg R_H$ in the measuring range. In the most adverse case, when $R_L = \infty$, a fractional error, α, in R_M will result in a fractional error of less than $\frac{\alpha R_H}{R_M(1+\alpha)}$ in the calculated value of V.

(2.1) Effect of Stray Capacitance

V_L is limited to a safe, but nevertheless much greater, value before flashover than after. Consequently, a relatively large charge, Q_{L0}, is stored on the stray capacitance C_L (see Fig. 1) before flashover: the corresponding charge on C_H is Q_{H0}. The construction of high-voltage resistance dividers is such that C_L is much larger than C_H, so that Q_{L0} is usually larger than Q_{H0}. This condition ($Q_{L0} > Q_{H0}$) will be considered in the present paper, but a similar treatment would apply if $Q_{L0} < Q_{H0}$.

Flashover connects C_H and the arc in parallel with C_L, and the charges Q_{L0} and Q_{H0} then contribute a component V_L' to V_L. V_L' has the maximum value $V_{L0}' = \frac{|Q_{L0}|-|Q_{H0}|}{C_L + C_H}$ and decays as the residual charge, $Q_0 = |Q_{L0}| - |Q_{H0}|$, discharges through R_H, R_L and R_M. The residual charge, Q_0, being positive, the reduction in V_L which should occur at flashover is delayed by V_L'. Now, R_M is much greater than R_H when V_L' is still quite large, so that further discharge of Q_0 is possible, in effect, only through R_H and R_L. Recording will therefore be inaccurate for a time of the order of the time-constant $T' = (C_L + C_H)R_HR_L/(R_H + R_L)$, which approximates to $R_HR_LC_L/(R_H + R_L)$, since $C_L \gg C_H$. After V_L' becomes negligible, the error due to stray capacitances falls to that due to their effect on the linear divider R_HR_L—the conventional case.

One method of eliminating V_L' is suggested by the expression for V_{L0}'. C_H could be increased deliberately, so that $Q_{H0} = Q_{L0}$, and $V_{L0}' = 0$. The appropriate value of C_H is $C_H' = C_L/(n_0 - 1)$, where n_0 is the divider ratio at flashover.

The value of C_H required to eliminate the error due to the effect of stray capacitances on the linear divider R_HR_L is $C_H'' = C_L/(n_\infty - 1)$, as in conventional mixed dividers. Now $n_\infty < n_0$, so that C_H'' is larger than C_H'. Consequently, if $C_H = C_H'$, recording would be more accurate than in the case of the linear divider R_HR_L.

If $C_H = C_H''$, recording would be inaccurate immediately after flashover, although very accurate recording would be obtained eventually. The protective action of the divider would be complicated by the relatively high value of C_H.

(3) DESIGN PROCEDURE

The following procedure is advocated for a first design.

R_H is selected first: it should be small, in order to keep v' small in the measuring range, and to provide a low-resistance discharge path to the stray capacitances. R_H is therefore given the minimum value, R_{Hm}, which does not interfere unduly with the performance of the test circuit.

Next, R_M is so selected that V_L shall not exceed a safe value at the maximum value of V, v' shall be small at the maximum value of V_L corresponding to the measuring range—in the most adverse case of $R_L = \infty$—and the stray capacitance of R_M (which increases C_L) shall have the minimum value consistent with the rating of R_M.

Finally, R_L is selected to give a suitable deflection on the oscillograph in the measuring range. If several divider ratios are required, it may be of advantage to vary R_H and R_L, while maintaining $(R_H + R_L) = 2R_{Hm}$ and $R_H \geqslant R_{Hm}$. In that case, v' and T' will not exceed half the value they would have if $R_H = R_{Hm}$ and $R_L = \infty$.

(4) DIVIDER DATA

The divider was designed to record an event having a peak voltage of 33 kV at flashover, and lasting for 150 microsec to 10 millisec. V_L had to be limited to 3 kV in the protective range; in the measuring range, $V_L < 500$ volts and $v' < 0{\cdot}1\%$.

In the normal use of this divider, either R_L was omitted and R_H set at 10 kilohms, or the sum of R_H and R_L was kept at 23 kilohms, R_H being not less than 10 kilohms (other values of R_H and R_L were used in some of the proving tests discussed in Section 5). The resistance of the silicon-carbide non-ohmic resistor, R_M, was 940 ohms at 3 kV and 1 megohm at 500 volts. The time-constant, T', which should be short compared with the duration of the briefest event to be recorded (150 microsec) did not, in fact, exceed 1 microsec, so that no lumped capacitance was used to increase C_H to C_H'.

R_H and R_L were constructed from identical woven-wire resistance ribbon, and the estimated accuracy of the divider was within $\pm 1\%$ after V_L' had become negligible (i.e. some 5 microsec after flashover).

(5) PROVING TESTS

(5.1) Effect of R_H on Protection of Oscillograph

A 35 kV long-duration pulse was applied to the divider, and the maximum value of V_L corresponding to different values of R_H was obtained by recording the voltage appearing across a fraction of R_L. Results are given in Fig. 3. The resistance characteristic of R_M was calculated from these data, and also from d.c. measurements at low voltages. It was found that over the range $0{\cdot}5 < V_L < 7{\cdot}2$ kV (i.e. over a considerably greater voltage range than that of Fig. 3), $R_M \simeq 7{\cdot}6 V_L^{-3{\cdot}32} \times 10^{14}$ ohms. This expression was then used to calculate the relation between R_H and the maximum value of V_L. The values of V_L obtained in this way were within $\pm 10\%$ of those given by direct experiment, as shown in Fig. 3. This justifies the use of an equation of the type $R_M = kV_L^{-m}$ to predict the operation of the divider for design purposes, as was done in connection with Fig. 2.

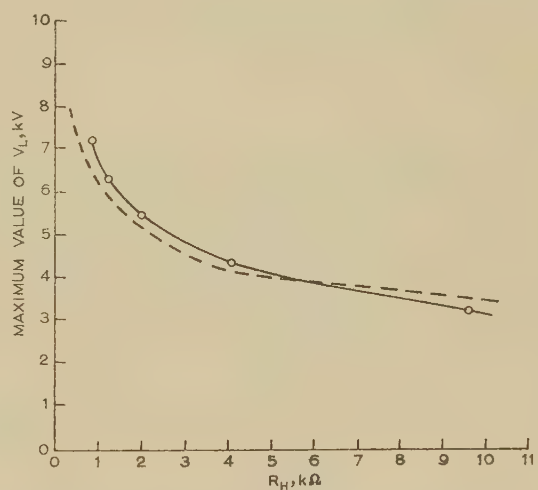

Fig. 3.—Relation between the maximum value of V_L, and the value of R_H, when a long-duration pulse with a peak value of 35 kV is applied across the divider ($R_L = 11{\cdot}9\,\text{k}\Omega$).

The continuous curve was obtained by experiment. The broken curve was obtained by calculation.

(5.2) Effect of R_H and C_L after Flashover

The circuit of Fig. 1 was used to verify experimentally the analysis of Section 2.1 relating to the effect of V_L'. C_H consisted only of stray capacitance and was so small that its effect

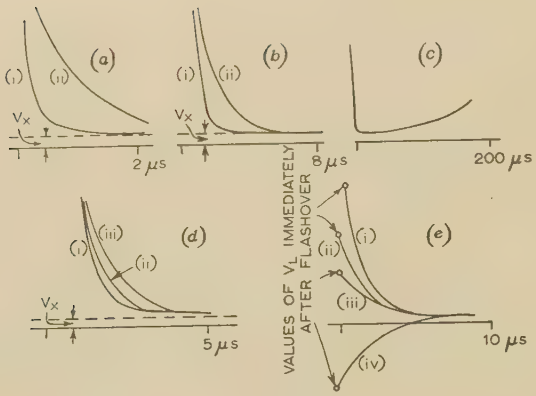

Fig. 4.—Curves of V_L to a base of time, traced from oscillograms.

(a) (i) $R_H = 1\,k\Omega$.
(ii) $R_H = 10\,k\Omega$.
The straight line corresponding to V_x has been obtained from Fig. 4(b).
$R_L = 1\,M\Omega$; no lumped C_H or C_L.

(b) (i) $R_H = 1\,k\Omega$.
(ii) $R_H = 10\,k\Omega$.
The Figure shows how the voltage V_x is obtained. The test-gap voltage V is assumed to fall to $n_\infty V_x$ at flashover, and to remain at that value until V'_L becomes negligible.
$R_L = 1\,M\Omega$; no lumped C_H or C_L.

(c) Curve obtained with $R_H = 1\,k\Omega$ and $10\,k\Omega$ (records identical).
$R_L = 1\,M\Omega$; no lumped C_H or C_L.

(d) (i) $C_L = 40\,\mu\mu F$.
(ii) $C_L = 50\,\mu\mu F$.
(iii) $C_L = 79\,\mu\mu F$.
V_x was obtained as for Fig. 4(a).
$R_H = 10\,k\Omega$; $R_L = 150\,k\Omega$; no lumped C_H.

(e) C_H is progressively increased for each of the subsequent curves (i), (ii), (iii) and (iv).
$R_H = 10\,k\Omega$; $R_L = 1\,M\Omega$. No lumped C_L.

and that of Q_{H0} were negligible. Also, $R_H \ll R_L$, so that $T' \simeq R_H C_L$.

The gap was flashed over by a 33 kV impulse, and oscillograms obtained with different values of R_H are given in Figs. 4(a)–4(c). They confirm that V_L falls more rapidly when T' is small (i.e. when R_H is small). An approximate quantitative analysis was attempted, assuming V to fall suddenly at flashover and to remain at the constant value $n_\infty V_x$ until V'_L had become negligible. V_L therefore tends to the constant value V_x, obtained from Fig. 4(b). The time constant T' was then taken as the time required for V_L to fall from any value $(V'_x + V_x)$ to $(0{\cdot}368 V'_x + V_x)$. Results obtained from the two curves of Fig. 4(a) are given in Table 1: they show that T' decreases less rapidly than R_H, owing, in all probability, to stray self-inductance becoming effective in controlling the discharge of C_L at the lower value of R_H.

Table 1

R_H	Time-constant T'
kΩ	μs
1	0·18
10	0·88

Table 2

Time Constants

$T' = R_H C_L$	T' (values obtained from oscillograms)
μs	μs
40	42
50	50
79	79

More consistent results were obtained in a similar test in which R_H was constant and C_L was increased by lumped capacitance. Curves from typical oscillograms are given in Fig. 4(d), and T' was measured as above. The stray capacitance component of C_L was then measured by Q-factor meter ($C_L = 40\,\mu\mu F$), and time-constants were estimated to within some 20% from $T' = R_H C_L$, the percentage error being nearly the same for all values of T'. Experimental and estimated results are compared in Table 2 and will be seen to be in close agreement. This justifies the discussion of Section 2.1 relating to the effect of V'_L.

(5.3) Effect of C_H on the Performance of a Divider

The circuit of Fig. 1 was used to verify qualitatively the effect on the performance of the divider after flashover of increasing C_H. Lumped C_H consisted of two 5 × 5 in aluminium plates: its value was varied by altering the distance between them and by introducing a sheet of Bakelite dielectric. Fig. 4(e) shows tracings obtained from oscillograms. Curves (i)–(iii) show that the values of V_L immediately after flashover decrease when C_H increases: this is because V'_{L0} decreases (Section 2.1). When C_H is given values greater than that at which $V'_{L0} = 0$, further increase in C_H results in V'_{L0} increasing in magnitude, its polarity being reversed: this is illustrated by curve (iv).

The above confirms qualitatively the discussion of Section 2.1 relating to the effect of C_H.

(5.4) Comparison of Non-ohmic Resistor with Gas Diode

A test was carried out with the circuit of Fig. 1, but with the non-ohmic resistor replaced by a gas diode. Oscillograms showed that during the first 2 or 3 microsec after flashover there was some variation in the voltage curves recorded on successive shots, the experimental conditions being the same. This inconsistency was ascribed to variations in the state of ionization of the gas diode (Section 1). However, when the oscillograph sweeps were sufficiently slow to record the whole of the event for which the divider was designed, no difference could be detected between records obtained under the same conditions, when the gas diode or the non-ohmic resistor was used. This was taken as additional confirmation of the performance of both types of non-linear divider.

(6) CONCLUSIONS

The analysis of a divider incorporating a non-linear resistor has been given, and has been verified experimentally. The divider has been used satisfactorily for over two years,[2] and a similar one is now in use at higher voltages.

Further work should aim at overcoming the main limitation of this type of divider, i.e. the voltage introduced immediately after flashover by the residual charges on the stray capacitances. The use of lumped capacitance C_H has been discussed in Section 2.1, where it was seen that if C_H had the appropriate value, the divider could be more accurate than a conventional resistance divider; alternately, a discharge path might be provided to the net residual charge, Q_0, by connecting a rectifier valve, having inter-electrode capacitance smaller than C'_H, in parallel with R_H.

(7) ACKNOWLEDGMENTS

The author wishes to acknowledge his indebtedness to Prof. F. M. Bruce for his interest in the work and advice in the preparation of the paper, and to Mr. A. S. Husbands for helpful discussions in the course of the work.

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Paper No. 1966 M
Feb. 1956

A NOTE ON THE THEORY OF OSCILLATING-ELECTRODE VOLTMETERS

By J. RAWCLIFFE, M.Sc.Tech., Associate Member.

(*The paper was first received* 24*th August, and in revised form* 24*th October*, 1955.)

SUMMARY

It has been tacitly assumed hitherto that the theory of the oscillating-electrode voltmeter derived for direct voltages applies equally well for alternating voltages if r.m.s. values are substituted for direct values. A rigorous treatment shows that this is not the case.

The measurement of peak values of high voltage by means of the sphere-gap is still common, in spite of the admitted errors involved, because of the simplicity of the apparatus required. For the measurement of high r.m.s. voltages the oscillating-electrode voltmeter also has the advantage of simplicity, and it is much more accurate.

Oscillating-electrode voltmeters are instruments for the absolute measurement of both alternating and direct voltage. They consist essentially of two electrode systems, one of which is free to oscillate with respect to the other. Both electrode systems form boundaries of an electric field which provides a restoring torque. In certain types a mechanical restoring torque is present in addition to the electric-field torque. If electrodes of simple geometrical configuration are used, a relatively simple analytical expression can be derived for the voltage to be measured in terms of the period of oscillation, the dimensions of the electrode system of the instrument, the inertia of the oscillating electrode and the free period of oscillation provided by the mechanical restoring torque, if any.

The first oscillating-electrode voltmeter was devised by Thornton,[1,2] who described the ellipsoid voltmeter in 1931 and estimated its accuracy to be within about 1 part in 10^3. The ellipsoid instrument consists of a conducting prolate ellipsoid, suspended by an insulating fibre and free to oscillate about its minor axis between two large parallel plates across which the voltage to be measured is applied. The development and detailed analysis of this instrument by Bruce[3] showed that an accuracy within 3 parts in 10^4 may be realized.

The significance of the new theory to be described in the paper depends on the magnitude of the ratio of the electrical spring constant to the inertia of the moving system, and if oscillating-electrode voltmeters had been developed no further than the ellipsoid variety, for which this ratio is small, the new theory would have been of negligible importance in practice. However, one of the disadvantages of the ellipsoid voltmeter is that it is difficult to manufacture, and in attempting to overcome these difficulties Bradshaw[4] has experimented with many forms of electrode voltmeter. In some of these the fixed and oscillating electrodes consist of a number of conducting spheres arranged as simple, torsional or compound pendulums. During more recent investigations along these lines it has been found possible to produce voltmeters having a much higher ratio of electrical spring constant to inertia than that of the ellipsoid voltmeter. Because of this, the following more rigorous analysis is of significance in the suitable choice of design parameters for future instruments.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
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The equation of motion for oscillating-electrode instruments is of the form

$$M_I\ddot{\theta} + R\dot{\theta} + (K_m + K_e)\theta = 0 \quad . \quad . \quad . \quad . \quad (1)$$

where M_I = Moment of inertia of the system.
R = Viscous damping constant.
K_m = Mechanical restoring torque per radian.
K_e = Restoring torque per radian due to the electric field.
θ = Angular displacement of the moving system.

The damping term $R\dot{\theta}$ is usually very small and can be accounted for by a small correction.

Therefore we have

$$M_I\ddot{\theta} + (K_m + K_e)\theta = 0 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The term K_e is a function of the applied voltage V, and it must remain constant for simple harmonic motion of the oscillating system, as also must K_m and M_I. For oscillating-electrode voltmeters the following relation is easily derived:[5]

$$K_e = \tfrac{1}{2}V^2K \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where V is the applied voltage and K is a constant depending on the form of the electrodes. For an electrode system consisting of simple shapes the analytical relations necessary to determine K can be expressed without much difficulty, and in most of the cases considered it has been shown that K remains constant with change of θ—at least for small amplitudes of oscillation.

With no voltage applied, eqn. (2) becomes

$$M_I\ddot{\theta} + (K_m)\theta = 0$$

A solution of this equation yields the free period of the instrument

$$T_0 = 2\pi\sqrt{\left(\frac{M_I}{K_m}\right)}$$

from which $$K_m = 4\pi^2M_I\left(\frac{1}{T_0^2}\right) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Similarly, when a direct voltage is applied, we obtain from eqn. (2) the period

$$T = 2\pi\sqrt{\left(\frac{M_I}{K_m + K_e}\right)}$$

from which $$K_m + K_e = 4\pi^2M_I\left(\frac{1}{T^2}\right) \quad . \quad . \quad . \quad . \quad (5)$$

Hence, by substitution of eqns. (3) and (4) in eqn. (5) an expression for the voltage is obtained in the form

$$V = \left[8\pi^2\frac{M_I}{K}\left(\frac{1}{T^2} - \frac{1}{T_0^2}\right)\right]^{1/2} \quad . \quad . \quad . \quad . \quad (6)$$

In the past, when the voltmeter has been used to measure

alternating voltage, it has been usual to substitute the r.m.s. value of the voltage for V when setting up the analytical relationships. This procedure is open to objection since an equation is produced which does not represent the physical actions taking place. If we represent the instantaneous value of the alternating voltage by $v = \hat{V}\sin\omega t$ we obtain from eqn. (3)

$$\begin{aligned} K_e &= \tfrac{1}{2}K\hat{V}^2\sin^2\omega t \\ &= \tfrac{1}{2}K\hat{V}^2[\tfrac{1}{2}(1-\cos 2\omega t)] \\ &= \tfrac{1}{2}KV^2 - \tfrac{1}{2}KV^2\cos 2\omega t \end{aligned}$$

where V is the r.m.s. value of the voltage.

Substituting this expression in eqn. (2),

$$M_I\ddot{\theta} + [(K_m + \tfrac{1}{2}KV^2) - \tfrac{1}{2}KV^2\cos 2\omega t]\theta = 0 \quad . \quad . \quad (7)$$

Let

$$2\omega t = z$$

$$2\omega dt = dz$$

$$\frac{d}{dt} = 2\omega\frac{d}{dz}$$

$$\dot{\theta} = \frac{d\theta}{dt} = 2\omega\frac{d\theta}{dz}$$

$$\ddot{\theta} = \frac{d^2\theta}{dt^2} = (2\omega)^2\frac{d^2\theta}{dz^2}$$

Therefore eqn. (7) may be rewritten

$$(2\omega)^2 M_I\frac{d^2\theta}{dz^2} + [(K_m + \tfrac{1}{2}KV^2) - \tfrac{1}{2}KV^2\cos z]\theta = 0$$

$$\frac{d^2\theta}{dz^2} + \left[\frac{K_m + \tfrac{1}{2}KV^2}{(2\omega)^2 M_I} - \frac{\tfrac{1}{2}KV^2}{(2\omega)^2 M_I}\cos z\right]\theta = 0 \quad (8)$$

$$\frac{d^2\theta}{dz^2} + [\delta + \epsilon\cos z]\theta = 0 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where δ and ϵ are the appropriate values in eqn. (8).

This is called Mathieu's equation[6] and it has no general solution in terms of elementary functions. It is a particular case of a linear type of the second order with periodic coefficients. Its solutions are stable, unstable, periodic or non-periodic according to the values assigned to δ and ϵ. Periodic solutions having periods 2π or 4π in z are defined by the values of δ and ϵ at transition from stable to unstable values.

On the old theory, the equation of motion is obtained by substituting eqn. (3) in eqn. (2), thus

$$M_I\ddot{\theta} + (K_m + \tfrac{1}{2}V^2K)\theta = 0$$

$$\ddot{\theta} + \left(\frac{K_m}{M_I} + \frac{\tfrac{1}{2}V^2K}{M_I}\right)\theta = 0 \quad . \quad . \quad . \quad (10)$$

$$\ddot{\theta} + (d+e)\theta = 0 \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where d and e are the appropriate values in eqn. (10).

If the alternating voltage is given on the new theory by $V_1 = f(T)$ and on the old theory by $V_2 = F(T)$, T being the period of the electrode in each case, the extent of the determinational error is the difference between $f(T)$, derived from eqn. (9), and $F(T)$, derived from eqn. (11). Eqn. (11) is, of course, correct for direct-voltage determinations.

The theory of Mathieu's equation[6] indicates that the magnitude of the error incurred by the substitution of r.m.s. values in eqn. (10) depends on the values of δ and ϵ and hence on the ratio K/M_I for any one voltage and frequency of the supply, since K_m is usually very small. From this it is seen that K/M_I is an essential design parameter.

The author is indebted to Mr. G. E. H. Reuter, of the Mathematics Department, University of Manchester, for obtaining a numerical solution of eqn. (9), using the parameters of Bruce's[3] ellipsoid voltmeter when operating at its maximum voltage. It was found that the determinational error in this case was of the order of 5 parts in 10^5. It is doubtful whether ellipsoid voltmeters can be built having substantially larger values of K/M_I, but this is not true of more recent types of oscillating-electrode voltmeter and hence some care must be exercised in the choice of this ratio in future designs.

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Feb. 1956

THE ELECTRIC STRENGTH OF HIGHLY COMPRESSED GASES

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SUMMARY

An experimental study of spark-breakdown potentials in compressed gases is reported.

Direct voltages up to 150 kV and electrodes giving a uniform field in the test gap were used. The gap length was in the range 1–3 mm.

The variation of spark-breakdown potentials with gas pressure is given for air and nitrogen in the pressure range 1–70 atmospheres. The effect of using aluminium instead of steel electrodes is shown.

Sulphur hexafluoride, carbon dioxide, and the fluoromethanes CCl_2F_2, $CHClF_2$, $CClF_3$ were similarly tested up to their saturation vapour pressures.

Comparison is made between the strengths of mixtures containing various proportions of air in nitrogen, with mixtures containing the same proportions of carbon dioxide in nitrogen.

Various mixtures of air and sulphur hexafluoride, nitrogen and sulphur hexafluoride, and nitrogen and CCl_2F_2 were tested.

Comparison is made with previous measurements in the limited range where this is possible. Paschen's Law and the criterion for spark-breakdown at high gas pressure are discussed.

(1) INTRODUCTION

The electric strength of a gaseous insulation medium may be increased in two ways: by increasing the gas pressure, and by using certain gases instead of air. Both methods are coming into increasing prominence with the use of very high voltages for research in physics and engineering and for the long-distance bulk transmission of electric power. Transformers, cables, switchgear, rectifier sets and condensers have been designed for gaseous insulation.[1–4] Compressed gases of various types and mixtures have been used extensively in the development of Van de Graaff electrostatic generators.[5]

Breakdown voltages in compressed gases have been measured over a period of many years, but there yet lacks a series of measurements enabling comparison to be made between the strengths of different gases over an extended pressure range. This paper records such measurements. As is discussed later, comparison with previous measurements is almost impossible because of the use of varying electrode arrangements. The present measurements are of breakdown under direct-voltage stress applied as a uniform field in the test gap.

A special laboratory in the Electrical Engineering Department of Queen Mary College, London, was designed for the installation of a small pressurized Van de Graaff generator, and a test pressure vessel for research into the electric strength of highly compressed gases. Although of a fundamental character, this work had practical bearing on the operation of the electrostatic generator. The first programme of work on this vessel was on positive point-to-plane discharges, and has been described by Foord.[6] This was followed by the breakdown studies in a uniform field gap which are described here.

(2) APPARATUS AND EXPERIMENTAL PROCEDURE

(2.1) Test Pressure Vessel and Electrode Assemblies

The main pressure vessel was that used and described by Foord.[6] Two electrode assemblies were used. One was that used by Foord, modified for uniform field work, and the first part of the work, that on gases available at low cost, was done with this assembly. To economize in the use of the more expensive gases used later, a second electrode assembly was used, mounted in the low-pressure vessel shown in Fig. 1. This vessel could

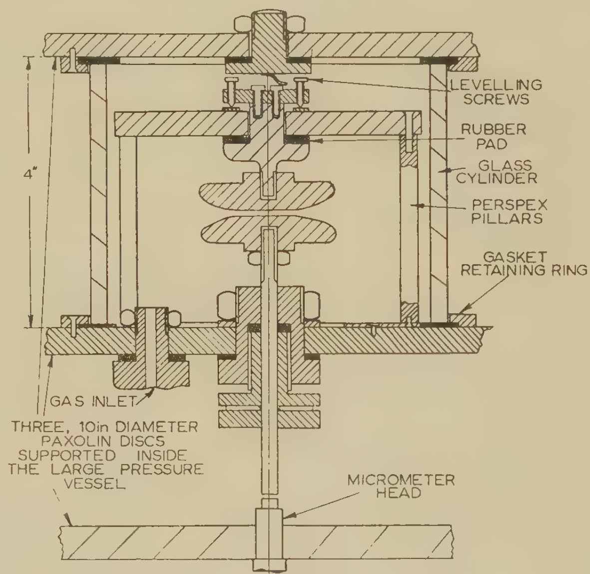

Fig. 1.—The low-pressure vessel.
Rubber seals.

withstand a pressure of about 1 atmosphere only and was used up to 75 atmospheres absolute pressure by providing a balancing pressure on the outside.

In both assemblies the electrodes were supported from the base of the pressure vessel so that distortion (elongation) of the vessel with increase of gas pressure did not affect the electrode gap-length. The gap was set by slip gauges in the first assembly and by micrometer in the second assembly. The electrodes were 9 cm in diameter with a 2·5 cm diameter flat in the first assembly and 5 cm in diameter with a 1·5 cm diameter flat in the second assembly. The electrode contour used by Bruce[7] was adopted.

(2.2) High-Voltage Supply and Pressure Equipment

High direct voltage up to 150 kV with a 1% 50 c/s ripple was supplied by a Cockcroft–Walton circuit, the input coming from a constant-voltage transformer. The output voltage was varied by two variable transformers in cascade in the primary of the h.t. transformer.

The high-pressure gas equipment was suitable for use up to

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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120 atmospheres. Cylinder gas was admitted into the pressure vessel through a sintered metal filter. When room air was used, the gas was compressed in a separator where most of the water vapour was condensed and was taken through a silica-gel container for further drying before admittance to the pressure vessel through the sintered metal filter. A backing pump operating through the high-pressure line could maintain a rough vacuum in the pressure vessel.

(2.3) Measurements

The voltage across the test gap was measured by reading the current in a chain of high-stability carbon resistance units immersed in oil. After tests on the individual units and the complete unit it was considered that the voltage measurement was accurate to within $\pm 1\%$ over the range 0–150 kV.

Currents as low as $0 \cdot 2 \mu A$ could be detected in the test gap. The temperature near the gap was recorded with a thermocouple. The pressure in the vessel was recorded with an accuracy of $\pm 1\%$ within the range 0–75 atmospheres absolute pressure.

(2.4) Experimental Procedure

(2.4.1) Procedure with the Main Pressure Vessel.

The electrodes were cleaned in the lathe using emery paper of increasing smoothness to grade 4/0. Dirt and emery particles were removed between changes in the grade of the emery paper, and finally by polishing with a rag moistened with carbon tetrachloride. After the interior of the vessel was cleaned with carbon tetrachloride, the electrode assembly, similarly cleaned, was mounted in the vessel.

The gap was levelled and set with a brass spacer. The vessel was evacuated to a pressure of 0·005 atmosphere absolute before nitrogen (oxygen free—see Section 4.1) was admitted to a pressure of 7 atmospheres absolute. This gas was tested at several decreasing pressures and the results were compared with those previously obtained for nitrogen (oxygen free). After initial low breakdown values which condition the electrodes, deviation from the standard curve of more than 5% was taken as indicating gaseous impurity, and the flushing was repeated.

After a further evacuation the gas for test was admitted. For the Arctons and sulphur hexafluoride a flushing at low pressure was done with the gas to be used. For less expensive gases this flushing was done to a higher pressure. After a final evacuation, readings were taken with increasing gas pressure. Time was allowed for the gas temperature to return to room temperature after each increment of pressure.

(2.4.2) Procedure with the Low-Pressure Vessel.

Electrode polishing was carried out as described above. The interior of the vessel was cleaned with carbon tetrachloride. The electrodes were aligned in the assembly and the gap set.

The main vessel was bolted down and both vessels were evacuated. The connection between the vessels was closed and nitrogen admitted to the low-pressure vessel and air to the main pressure vessel, maintaining an excess pressure in the inner vessel of 1 atmosphere. The gap was tested at about 7 atmospheres pressure and, after conditioning, compared with the standard nitrogen gap. The flushing procedure followed that described for the main vessels, the two vessels remaining sealed from each other unless evacuation was required. Air was used to balance the pressure in the low-pressure vessel. At all times the differential pressure in the inner vessel was kept positive unless it was to be evacuated, in which case the outer vessel was evacuated first.

The gap length was independent of the pressure, provided that this did not exceed 1 atmosphere. As an additional safeguard, readings were taken for a constant value of this differential pressure during the test. The setting of the gap was accurate to 0·001 cm, but checking of the gap after each test showed that an overall accuracy not greater than 0·002 cm can be claimed. The maximum error for the smallest gap used was therefore 2%.

(3) EXPERIMENTAL RESULTS

(3.1) Factors affecting the Method of Test

It was found that, with the electrodes properly aligned, sparking occurred in a random fashion between their flat areas. This was the case for the electrodes of each pressure vessel. In comparing the tests with different-sized electrodes no electrode-area effect could be detected.

Following the practice in operation for the Van de Graaff generator in the laboratory, gas mixtures were obtained by adding one gas, by the required pressure increments, to an initial pressure of the other. Back diffusion during the admission of gas was reduced by admitting gas only from a cylinder at a pressure considerably higher than that in the pressure vessel. This method gives a more accurate measurement of the gas mixture used than if an attempt is made to test constant-percentage mixtures at different pressures by admitting the correct quantities of the gases to give the maximum pressure, and then taking readings at lower pressures by allowing the mixture to escape. When this method is used it is customary to ignore the different diffusion rates on release of gases of different molecular weight.

The nitrogen used throughout the experiments contained less than 10 volumes per million of oxygen. It was found by Foord[6] not to exhibit the phenomenon resulting in a maximum in the breakdown-strength/pressure characteristic for a positive point-to-plane electrode configuration. Commercial nitrogen does exhibit this maximum.[8] On the other hand, some visible corona occurred at low pressures, contrary to the results obtained by Weissler[9] in specially prepared pure nitrogen.

From the flushing procedure outlined above the residual oxygen and nitrogen content in the vessel at the commencement of a test can be calculated. If, after the routine flushing procedure, the test gas is admitted to a pressure of one atmosphere it will contain 6·5 volumes per thousand of nitrogen and 1·2 volumes per million of oxygen. The maximum contamination due to CCl_4 vapour would occur if the residual gas remaining after the first evacuation was 100% CCl_4. This would give a contamination of 6 volumes per million of CCl_4.

Curve (*b*) of Fig. 2 is an example of the conditioning effect discussed in detail by Howell.[10] It is seen that, for a 3 mm gap, a curve may be taken of general shape similar to the one taken with conditioned electrodes [curve (*a*)] but lying at significantly lower strength for almost the entire pressure range. Several breakdown-voltage readings were taken at each pressure and the point plotted is the average value. Each reading was obtained by increasing the voltage comparatively rapidly up to a value of about 10 kV below the expected breakdown figure, and then applying a gradual increase by means of the fine-control variable transformer at a rate of approximately 10 kV per minute, until a spark occurred. This voltage was then held for several minutes and the rate of sparking determined. A typical reading is given in Table 1.

Table 1

RATE OF SPARKING AT CONSTANT VOLTAGE IN COMPRESSED NITROGEN

Reading of microammeter in series with h.v. resistor	Number of sparks in successive minutes
270	1, 0, 2, 0, 1, 1, 0

Occasional sparks occurred at voltages as much as 10 kV below such a figure, but they would be isolated and could not be repeated simply by maintaining the voltage. Such sparks were not counted as part of the readings. When a 1 min withstand voltage was known approximately, an alternative method of voltage application was to bring the voltage to within about 2 kV of this figure, and maintain it for 1 min. If one or more sparks occurred in this minute a reading similar to the one in the Table would be obtained. In the absence of a spark the voltage was raised by approximately 2 kV and the process repeated. The readings obtained by the first method are not 1 min withstand voltages because the voltage was increased steadily until a spark occurred, but it was found that, provided the rate of rise was not much faster than that mentioned, the two methods gave the same results.

Goossens[11] found no effect of irradiation on the spark-breakdown potentials of gases above a pressure of 6 atmospheres. In the present work the scatter of the breakdown-voltage measurements was not measurable at pressures below 6 atmospheres, and it is therefore not considered that the lack of irradiation affects the results.

Changing the polarity of the applied voltage likewise caused no measurable difference in the breakdown readings.

The use of a fan fitted in the bottom of the vessel caused sparks to occur at lower voltages and greatly increased the sparking rate, if switched on whilst a reading was being taken. This effect occurred in later tests with gas mixtures and is considered to be due to the presence of dust particles or other impurities which, if present in the gap initially, will give the low breakdown voltages mentioned above which will recur if the particles are continually swept into the gap. Unlike the experience of Skilling and Brenner,[12] it was not found that stirring a gas mixture was necessary to obtain either consistent or characteristic results with the apparatus used.

In all the following tests the electrodes were conditioned by sparking at a fairly high sparking rate and high applied voltage after they had been newly polished and set up in the vessel. Conditioning was considered complete when the repeated increase of voltage above a figure with a sparking rate of about 1 spark/min always caused rapid sparking. Conditioning was usually combined with the standard flushing procedure.

Curve (*a*) of Fig. 2 shows the degree of scatter of the breakdown readings of a particular test with conditioned electrodes. Five or 10 readings were taken at each pressure, which was the

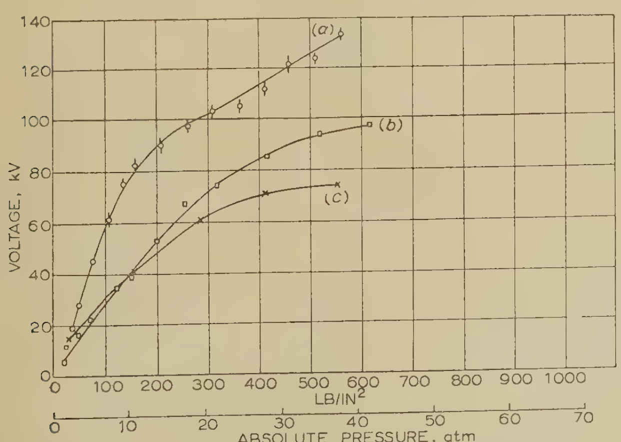

Fig. 2.—The spark-breakdown strength of nitrogen.

Electrode material: bright mild steel; gap length, 3 mm.

(*a*) Conditioned electrodes showing scatter obtained during one test.
(*b*) Unconditioned electrodes.
(*c*) Electrodes subjected to glow discharge before test.

standard practice for all the following tests. Readings were separated by 1 min intervals. The fan was not used in this test and every spark was recorded. Some of the sparks at voltages below the mean for a certain pressure occurred singly, but the majority of breakdowns were in the form of a burst of sparks. For the higher voltages at constant pressure the initial burst would be followed by a rapid succession of others and the voltage was quickly reduced immediately these readings were taken.

When aluminium electrodes were used it was found that damage to the electrodes by sparking caused a lowering of the sparking voltage, so a second water resistor, also of 5 megohms approximately, was inserted in the h.v. line between the power unit and the pressure vessel. This was fitted immediately above the high-voltage bushing in order to reduce both the limiting discharge current in the circuit and the stray capacitance, which discharged straight through the gap without the damping of a resistor.

Fig. 3 illustrates the reproducibility of the 3 mm nitrogen characteristic. Four curves are shown, each of which is subject

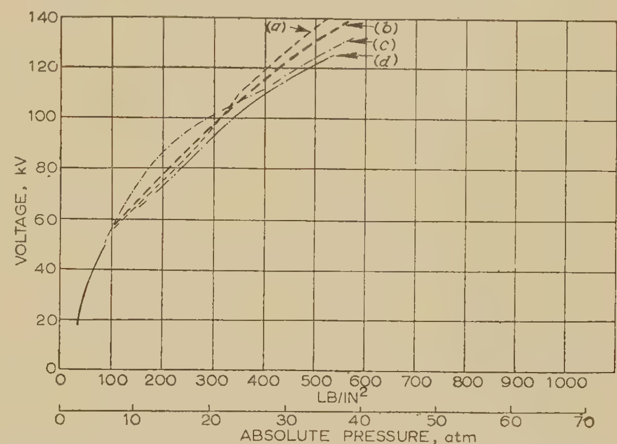

Fig. 3.—The spark-breakdown strength of nitrogen, accuracy of reproduction.

Electrode material: bright mild steel; gap length *G*, 3 mm.

to the degree of scatter shown in curve (*a*) of Fig. 2. After obtaining curve (*a*) (Fig. 3) according to the procedure described in Section 2.4, the vessel was evacuated and nitrogen readmitted, giving the result shown in curve (*b*). The gap was then dismantled, the electrodes polished and cleaned and the gap reset; the vessel was evacuated and then flushed with nitrogen and the electrodes conditioned. After a second evacuation nitrogen was admitted and curve (*c*) was obtained. Two tests were then carried out using air, but the electrodes were not disturbed again before taking curve (*d*).

Values of the total scatter between the curves are given in Table 2.

Table 2

SCATTER OF SPARK-BREAKDOWN READINGS IN NITROGEN

Gap length	Pressure, atmospheres absolute					
	10	20	70	10	20	70
	Scatter on individual points during one test			Total scatter on repeated tests		
mm	%	%	%	%	%	%
1	5	7	8	12	16	8
2	5	8	—	—	—	—
3	5	9	—	8	10	—

Before the commencement of the test shown in curve (*c*) of Fig. 2 the vessel was evacuated after a previous test with nitrogen to a pressure of 0·005 atmosphere and a glow discharge of 10 mA was run for 40 min, the polarity being changed several times. Because evacuation was continued for several hours it is likely that the oxygen content of this residual gas was higher than normal. The resulting nitrogen characteristic is seen to have approximately half the strength at corresponding pressures of that for electrodes prepared in the normal way.

(3.2) The Electric Strength of Some Common Gases and of Mixtures thereof

Figs. 4, 5 and 6 record the results of tests on nitrogen, air and carbon dioxide respectively. The scatter in the breakdown

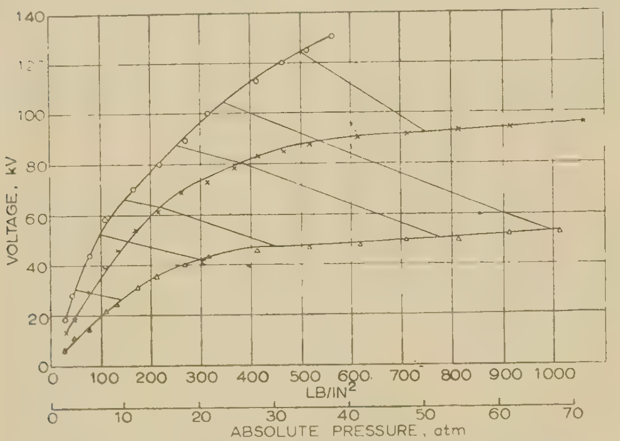

Fig. 4.—The spark-breakdown strength of nitrogen.

Electrode material: bright mild steel; gap lengths, 1, 2 and 3 mm.
Curves for which individual points are not shown are for constant values of the product [gas pressure × gap length (*pd*)].

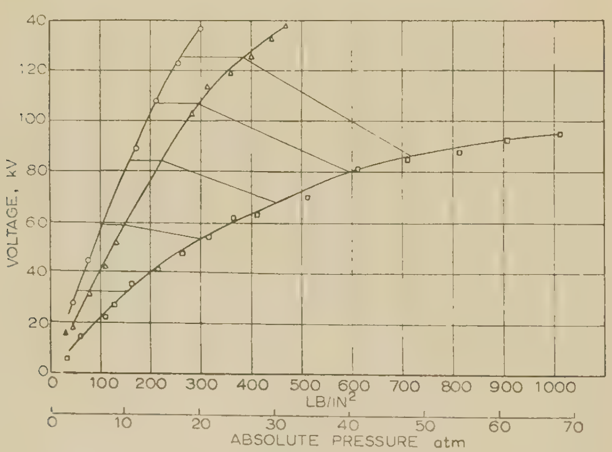

Fig. 5.—The spark-breakdown strength of air.

Electrode material: bright mild steel; gap lengths *G*, 1, 2 and 3 mm.
Curves for which individual points are not shown are for constant values of the product *pd*.

voltage of nitrogen at different pressures is shown in Table 2. In air the total scatter rose to 5% at the highest pressure. No steady pre-breakdown current was detected in air or nitrogen. Figs. 7 and 8 show the effects of using mixtures of nitrogen plus air and carbon dioxide respectively.

When carbon dioxide was tested the gas was forced into the inner pressure vessel until it liquefied, and additional readings were taken in the liquid phase. An increase in strength was

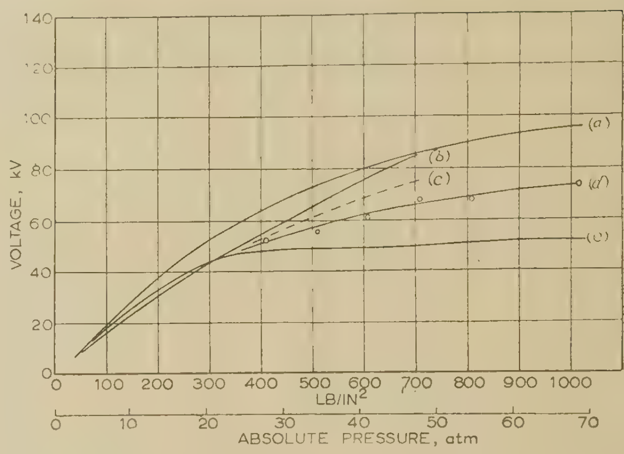

Fig. 6.—A comparison of the electric strengths of some common gases.

Electrode material: bright mild steel; gap length *G*, 1 mm.
(*a*) Air.
(*b*) Carbon dioxide.
(*c*) Carbon dioxide with abscissa representing a linear increase of gas density.
(*d*) Nitrogen added to an initial pressure of 7 atmospheres carbon dioxide.
(*e*) Nitrogen.

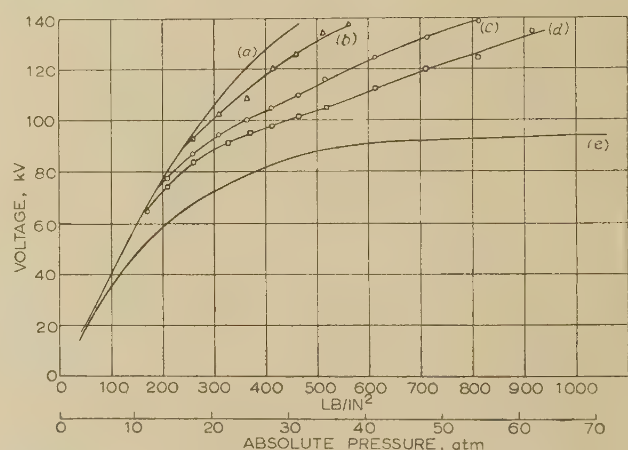

Fig. 7.—The electric strengths of air–nitrogen mixtures.

Electrode material: bright mild steel; gap length *G*, 2 mm.
(*a*) Air.
(*b*) 5 atmospheres air.
(*c*) 2 atmospheres air.
(*d*) 1 atmosphere air.
(*e*) Nitrogen.
The pressures refer to initial pressures of air, to which nitrogen was added.

recorded until just before the saturated vapour pressure was reached. At this point the scatter, which had been negligible, became about 10%; there was no further increase in breakdown voltage, and bright lines (taken to be reflection due to bubbles) crossed the gap at breakdown. The pre-breakdown current reached between 1 and 3 μA at breakdown.

When the gap was immersed in the liquid bubbles were not seen at breakdown, but the breakdown values were between 32 and 41·5 kV, and sparks seemed instrumental in causing currents of tens of microamperes in the gap. Even after a pause of several minutes currents were established in the gap of quite high values before a spark occurred. If the voltage was not further increased these currents would decrease in an approximately exponential fashion until re-established by a spark. A specimen reading is given in Table 3. The voltage was steadily increased to 32 kV, when a spark occurred. With the voltage

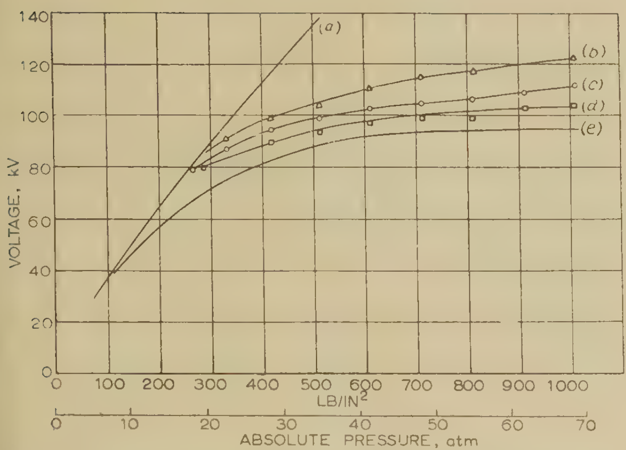

Fig. 8.—The electric strengths of carbon-dioxide–nitrogen mixtures.

Electrode material: bright mild steel; gap length G, 2 mm.

(*a*) Carbon dioxide.
(*b*) 5 atmospheres carbon dioxide.
(*c*) 2 atmospheres carbon dioxide.
(*d*) 1 atmosphere carbon dioxide.
(*e*) Nitrogen.

The pressures refer to initial pressures of carbon dioxide, to which nitrogen was added.

constant, current readings were then taken every 10 sec and further sparks noted. The gap spacing was 1 mm.

Table 3

CONDUCTION CURRENT AND SPARKING RATE IN LIQUID CO_2 STRESSED TO 320 kV/cm

	Readings at 10 sec intervals
Current, μA ..	23—10—15—10—8—7—7—15
No. of sparks ..	1 2 1

(3.3) The Electric Strength of Sulphur Hexafluoride and of Some Halogen Derivatives of Methane, and of Mixtures of these Gases with Air and Nitrogen

Sulphur Hexafluoride.

Fig. 9 shows the result of a test with a gap length of 1 mm. The scatter is very small until near the saturated vapour pressure when it reaches 5%. Near this pressure, the breakdown voltage shows a smaller rate of increase with pressure. The pre-breakdown current is only a fraction of a microampere at 100 kV.

In the liquid phase the breakdown voltage fell approximately 40% and had a scatter of about 15%. Gap currents were higher than in the vapour phase. A typical reading of gap current

Table 4

CONDUCTION CURRENT AND SPARKING RATE IN LIQUID SF_6 STRESSED AT 900 kV/cm

Gap current, μA, read at minute intervals	6	7	5	6	6	5	4	10	7	6	4
No. of sparks per minute	12	3	2	6	4	0	7	4	2	0	

and sparking rate at a constant applied voltage in the liquid phase is shown in Table 4.

After sufficient conditioning a voltage nearly as high as the maximum in the vapour phase could be held across the gap. In

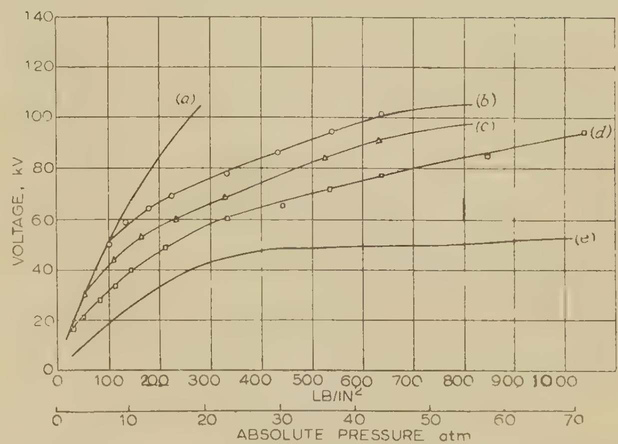

Fig. 9.—The electric strengths of sulphur hexafluoride–nitrogen mixtures.

Electrode material: bright mild steel; gap length G, 1 mm.

(*a*) Sulphur hexafluoride.
(*b*) 7 atmospheres sulphur hexafluoride.
(*c*) 3·5 atmospheres sulphur hexafluoride.
(*d*) 0·7 atmosphere sulphur hexafluoride.
(*e*) Nitrogen.

The pressures refer to initial pressures of sulphur hexafluoride, to which nitrogen was added.

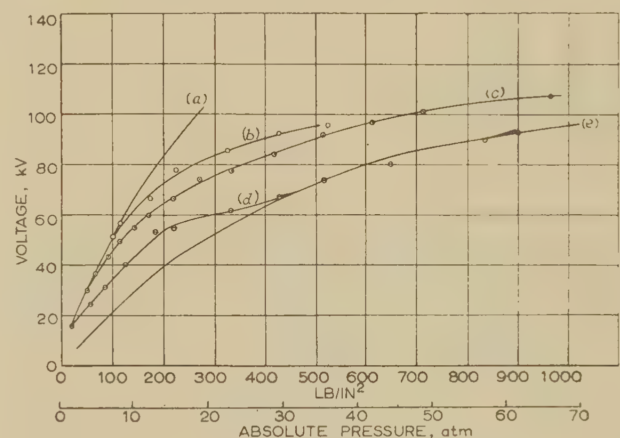

Fig. 10.—The electric strengths of sulphur hexafluoride–air mixtures.

Electrode material: bright mild steel; gap length G, 1 mm.

(*a*) Sulphur hexafluoride.
(*b*) 7 atmospheres sulphur hexafluoride.
(*c*) 3·5 atmospheres sulphur hexafluoride.
(*d*) 0·7 atmosphere sulphur hexafluoride.
(*e*) Air.

The pressures refer to initial pressures of sulphur hexafluoride, to which air was added.

the course of this conditioning, during which a copious stream of bubbles was evolved, the pressure of the vapour rose by 0·5 atmosphere to 21 atmospheres. Figs. 9 and 10 show the breakdown strength of mixtures of sulphur hexafluoride with nitrogen and air, respectively.

Arcton 3 (*CF_3Cl—Freon* 13).

This gas was tested to a pressure of 32 atmospheres in the vapour phase (Fig. 11). Representative readings for breakdown voltage and pre-breakdown current in various states are given in Table 5.

Arcton 4 (*CHF_2Cl—Freon* 22).

This gas had a saturated vapour pressure of 10 atmospheres at the room temperature of the test. At this pressure, when liquid was present at the bottom of the cell, the fluid was seen

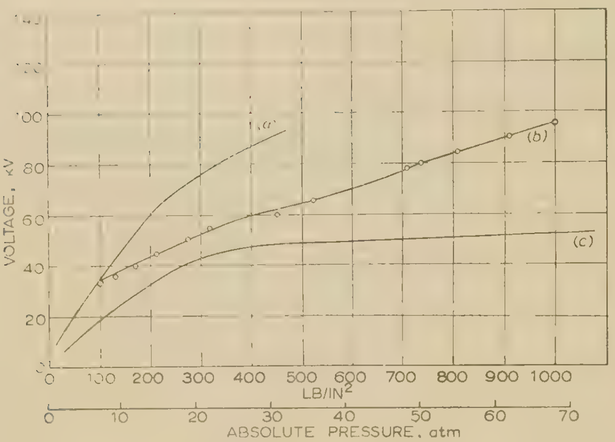

Fig. 11.—The electric strengths of CF_3Cl–nitrogen mixtures.

Electrode material: bright mild steel; gap length *G*, 1 mm.

(*a*) Arcton 3, CF_3Cl.
(*b*) Nitrogen added to an initial pressure of 7 atmospheres CF_3Cl.
(*c*) Nitrogen.

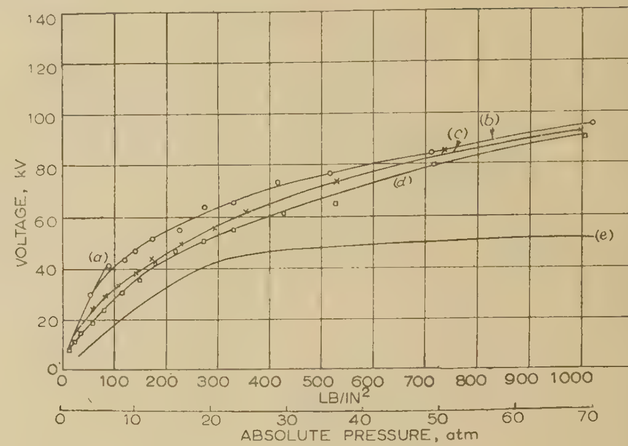

Fig. 12.—The electric strength of CCl_2F_2–nitrogen mixtures.

Electrode material: bright mild steel; gap length *G*, 1 mm.

(*a*) Arcton 6, CCl_2F_2.
(*b*) 3·5 atmospheres CCl_2F_2.
(*c*) 2 atmospheres CCl_2F_2.
(*d*) 0·7 atmosphere CCl_2F_2.
(*e*) Nitrogen.

The pressures refer to initial pressures of CCl_2F_2, to which nitrogen was added.

Table 5

Spark-Breakdown Characteristics of CF_3Cl in a 1 mm Gap

State of fluid	Well below saturation	Saturated vapour	Liquid
Pressure, atmospheres absolute	15	32	40
Breakdown voltage, kV ..	64	35–94	40
Scatter, %	3	100	12
Pre-breakdown current, μA ..	0·4	0·8 at 35 kV	2

to be attacking the Perspex rods which support the upper electrode. The test was therefore discontinued and measurements were not taken into the liquid phase. The Paxolin, metal and glass parts of the cell were unaffected by the fluid. The voltage maximum was 40 kV and from 20 kV upwards pre-breakdown currents were measured, increasing to 3 μA. Above 25 kV the scatter became noticeable, increasing to 10% at 40 kV. The relative electric strength of this gas is given in Table 6 (Section 4.1).

Arcton 6 (*CF_2Cl_2—Freon* 12).

Readings in the vapour phase for Arcton 6 could be taken only up to a pressure of 5·6 atmospheres absolute (Fig. 12). At 4·7 atmospheres, when the breakdown voltage was 39 kV, the gap currents were only of the order of tenths of microamperes, but when, at the vapour pressure, liquid began to condense on the electrodes, the current rose to between 20 and 30 μA with a breakdown voltage of 43 kV.

Measurements in the liquid phase again showed a low breakdown voltage, readings varying from 24 to 38 kV. Currents were higher than in the unsaturated vapour phase and were greatly increased by sparking. There was a limited evolution of bubbles due to voltage application, but no voltage conditioning effect was obtained. Only small temporary changes in temperature were observed during the tests on liquids. The electric strengths of Arcton 6–nitrogen mixtures are shown in Fig. 12.

(3.4) The Effect of Electrode Material on the Electric Strength of Gases

The effect was investigated with two types of gas (Fig. 13). Nitrogen was used because it has the lowest electric strength of the gases tested, and a mixture of 3·5 atmospheres of sulphur hexafluoride plus air was used because its electric strength was relatively high and it could be tested up to the maximum pressure.

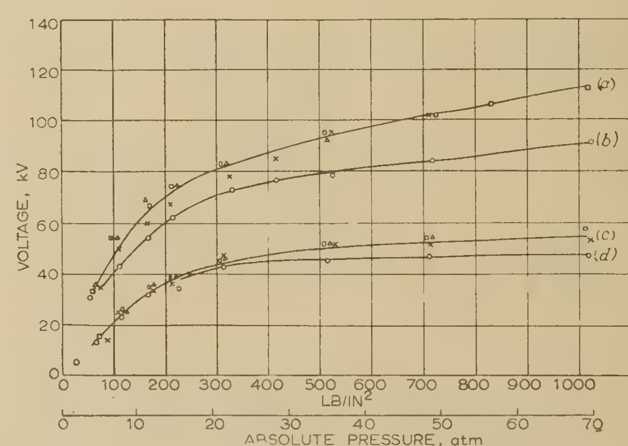

Fig. 13.—The effect of electrode material on the electric strength of gases.

○ Aluminium electrodes.
□ Copper electrodes.
△ Stainless-steel electrodes.
× Bright-mild-steel electrodes.
Gap length, 1 mm.

(*a*) and (*b*) Air added to an initial pressure of 3·5 atmospheres sulphur hexafluoride.
(*c*) and (*d*) Nitrogen.

The electrodes were prepared in the same way as for the previous tests, with the exception of the copper electrodes, which were immersed in a de-greasing bath of trichlorethylene vapour after polishing. The flushing and electrode conditioning procedures were also the same.

In nitrogen, the scatter with the stainless-steel electrodes was greater than with mild-steel electrodes. At the higher pressures it was 10%, and no consistent difference in strength can be inferred from the results between the two metals. Copper electrodes gave a much smaller scatter and, at the highest pressures, gave a strength approximately 10% greater than the mild-steel electrodes. The scatter for the aluminium electrodes was of the same order as for those of mild steel, and at the highest pressures these electrodes gave a strength approximately 10% below that for mild-steel electrodes.

Larger variations in strength over a greater pressure range are obtained when the gas mixture of high electric strength is used. Variation at low pressure between electrodes of mild steel, stainless steel and copper, though of the order of 10%, are considered likely to be due to relatively small variation in gas content between the tests. Pre-breakdown currents, detected above approximately 70 kV, remained of the order of 2 or 3 tenths of a microampere at the highest voltage for electrodes of these three metals. Furthermore, it is seen that in the upper pressure range there is no variation in strength greater than the scatter on individual readings.

The lower strength recorded with aluminium electrodes amounts, at the highest pressure, to 15% below that found with the other metals and was accompanied by gap currents, detected at 50 kV, which reached 1 μA at 85 kV. For these reasons it is concluded that the lower strength is significant and is an electrode effect.

The effect of aluminium in place of mild-steel electrodes is shown in more detail in Figs. 14, 15, 16, 17. No steady pre-breakdown current was detected in these tests. To supplement the data of Fig. 16, readings were taken in air at 28 atmospheres pressure. The breakdown gradient at the electrodes was 1·25 MV/cm with a steel cathode and aluminium anode, and remained unchanged when the anode and cathode materials were reversed. The same result is seen to occur for nitrogen (Fig. 16).

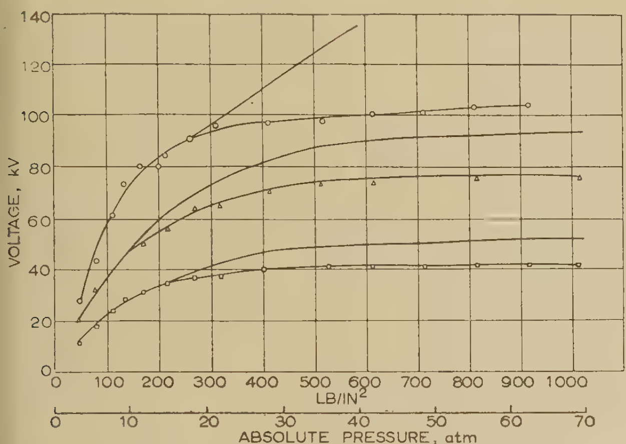

Fig. 14.—The spark-breakdown strength of nitrogen with aluminium electrodes.

Electrode material: aluminium; gap lengths *G*, 1, 2 and 3 mm.
Curves for which individual points are not shown were obtained using bright-mild-steel electrodes.

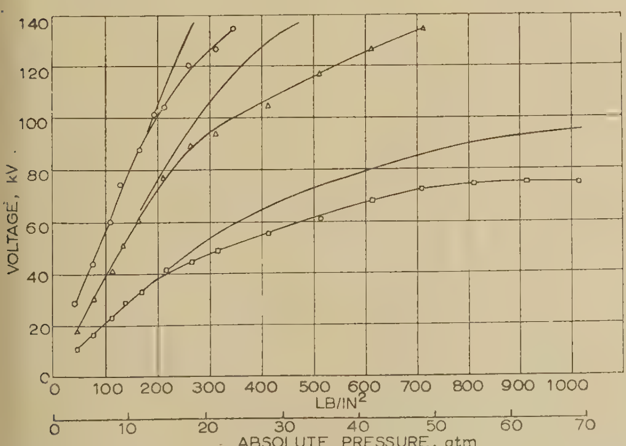

Fig. 15.—The spark-breakdown strength of air with aluminium electrodes.

Electrode material: aluminium; gap lengths *G*, 1, 2 and 3 mm.
Curves for which individual points are not shown were obtained using bright-mild-steel electrodes.

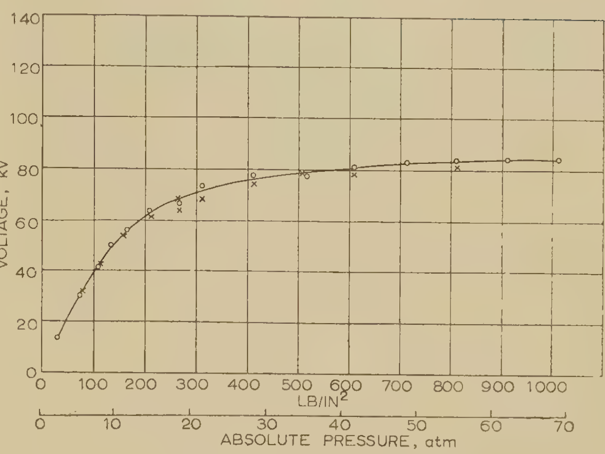

Fig. 16.—The spark-breakdown strength of nitrogen with electrodes of different metals.

Gap length, 2 mm.
×—× Anode, aluminium: cathode, bright mild steel.
○—○ Anode, bright mild steel: cathode, aluminium.

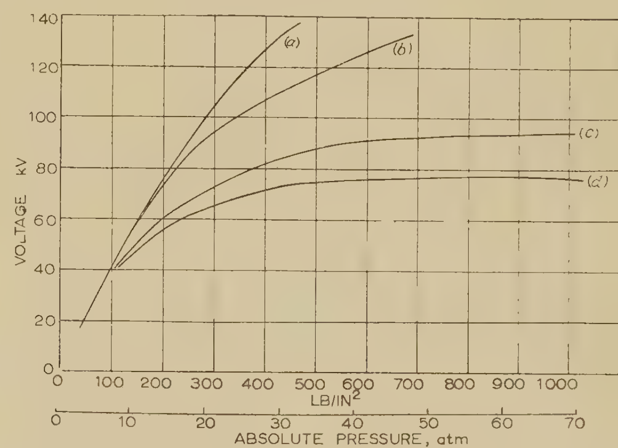

Fig. 17.—Summary of results with air and nitrogen and different electrode materials.

Gap length, 2 mm.
(*a*) Air; bright-mild-steel electrodes.
(*b*) Air; aluminium electrodes.
(*c*) Nitrogen: bright-mild-steel electrodes.
(*d*) Nitrogen; aluminium electrodes.

(4) DISCUSSION OF RESULTS

(4.1) Comparison with Other Workers

The nitrogen tested is almost invariably commercial nitrogen which contains a significant percentage of oxygen. As seen from Fig. 7, the oxygen content makes an important difference to the electric strength at the high pressures. Finkelmann[13] shows a marked difference in strength between air and nitrogen for gap lengths of from 1 to 3 mm and pressures up to 20 atmospheres, whilst Zeier[14] shows little difference in strength for a 1 mm gap up to a pressure of 40 atmospheres. It is to be expected that, where the oxygen content is not fixed, measurements of electric strength in nitrogen will lose their value above a pressure of

about 10 atmospheres. For these reasons it has not been found possible to make any direct comparisons for nitrogen.

Dry air has been tested more thoroughly than any other gas. Fig. 18 shows the results obtained using steel electrodes giving a

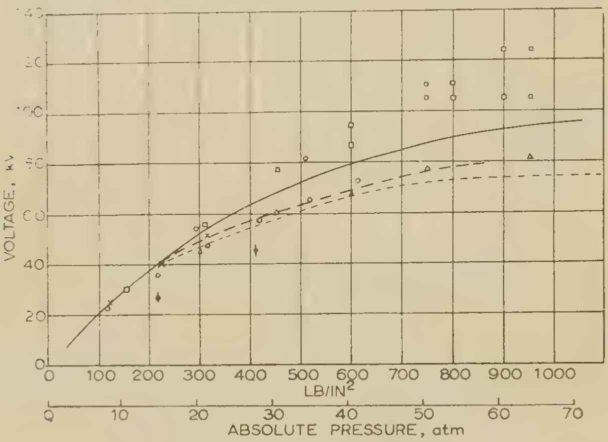

Fig. 18.—The electric strength of air according to several workers.
Gap length normalized to 1 mm.

Symbol	Worker	Voltage	Electrodes	Reference
○	Howell	D.C.	Steel planes	10
×	Skilling and Brenner	A.C.	Steel spheres	12
□	Félici and Marchal	D.C.	Stainless-steel planes	16
△	Félici and Marchal	D.C.	Iron planes	16
○	Zeier	D.C.	15 mm diameter spheres	14
ϕ	Trump *et al.*	D.C.	Stainless-steel planes	15
—'—	Boulloud	D.C.	Aluminium planes	26
- - -	Cohen	D.C.	Bright-mild-steel planes	—
——	Cohen	D.C.	Aluminium planes	—

uniform field gap. Except for the result of Trump[15] the tests were carried out using a gap of approximately 1 mm, and in all cases have been corrected for plotting to apply to a 1 mm gap. Trump used much higher voltages and his minimum gap length was ¼ in.

It appeared justifiable to extrapolate Trump's results to account for smaller gap lengths, because it is generally found in this range that, at constant pressure, there is a linear relationship between gap length and breakdown voltages. This is shown to be the case for the present investigation in Fig. 19. Zeier[14] has demonstrated the linearity for gaps in the range 0·1–1·0 mm and Howell[10] verifies it for gaps between 1·0 and 25 mm in length. Trump's results confirmed this fact in the range 6–18 mm. It may be concluded that there is some difference in the experimental arrangement which is causing these large divergences from the other results. Trump used an electrostatic generator as his test cell, and it may be suggested that consequent gaseous impurities lowered the breakdown values as well as increasing the scatter of the readings.

The values given in tables by Félici and Marchal[16] show both a much larger scatter than that noted in the present work and a far greater sensitivity to electrode material. They are the only results covering the whole pressure range, and the present results lie between their values for stainless-steel and iron electrodes. In the other cases the agreement is within the variation obtained by the different observers and supports the accuracy of the tests here presented.

Taking the gases as a whole, it is possible to compare relative electric strengths only at comparatively low pressures. This is done for the gases tested, and for some which are closely related chemically, in Table 6.

Very few direct comparisons, in which all the main experimental factors are the same, can be made. It is generally considered that the 50 or 60 c/s a.c. breakdown strength of a uniform field gap is the same as the d.c. breakdown strength and, in the pressure range noted, little difference is observed between the electric strengths of air and nitrogen. Bearing these points in mind, we may assume that most of the figures for any one gas are roughly comparable, provided that the electrodes give a uniform field.

Unfortunately in the two cases[20,21] where spherical electrodes are used the spacing cannot be taken as small compared to the sphere diameter. Foord[25] found the relative electric strength

Table 6

THE ELECTRIC STRENGTH OF GASES RELATIVE TO AIR

Worker	Present work	Hochberg and Sandberg		Charlton and Cooper	Camillie and Chapman		Adams		McCormick and Craggs	Hochberg and Glikina	Bontsch-Brunevitch *et al.*	Approximate vapour pressure at room temperature
Gas pressure (atmospheres)	3	1‡	1‡	1*	1*	3*	1	3	1*	Up to 10*	—*	
Reference	—	17	18	19	20	20	21	21	22	23	24	atmospheres
SF_6 ..	2·7	2·49	2·3–2·5		2·0	1·5	2·7	2·2	1·85	2·5	2·2	18
CCl_4 ..		6·36	6·3									0·14
CCl_3F ..		4·47	3–4·4	3·0†					2·65			0·95
CCl_2F_2 ..	2·7	2·56	2·4–2·5	2·4	2·4	1·75			2·05			5·7
CF_3Cl ..	1·65				1·65	1·3			1·22			27
CF_4 ..			1·1		1·1	1·1	2·2	1·7	0·92			—
$CHCl_3$ ..		4·24										0·24
$CHCl_2F$ ..				1·33								71
CHF_2Cl ..	1·4				1·2	0·77						8
CHF_3 ..					0·8	0·82						40
CH_2ClF ..				1·03								—
CH_3Cl ..		0·91		1·06								—
CH_4 ..		0·84										—

* Relative to nitrogen.
† Nitrogen added to atmospheric pressure.
‡ From extrapolated Paschen curves.

Reference 20. 60 c/s a.c. between 1 in diameter spheres spaced ¼ in.
Reference 21. 50 c/s a.c. between ½ in diameter spheres spaced 0·2–0·5 cm.
All other tests used direct current and electrodes giving a uniform field.

of CCl_2F_2 at atmospheric pressure to be 2·7 for the uniform field and 2·25 for the highly divergent field configuration with which nearly all his work was done. There is, however, no consistent trend in the results reported in the two former references which might be ascribed to a non-uniformity in the field. But in the same references there were surprising variations in the relative electric strength of all the gases noted, except CF_4, occurring over the pressure range from 1 to 3 atmospheres. As is shown in Table 7, such marked differences in so limited a pressure range were not noted in the present work, and it may be more reasonable to ascribe this feature of these results to the lack of field uniformity.

The variation with pressure of the electric strengths of the gases tested, relative to air, is shown in Table 7.

Table 7

VARIATION OF THE ELECTRIC STRENGTH OF GASES WITH PRESSURE, RELATIVE TO AIR

Pressure, atmospheres absolute	3	7	10	13	17	20	27	70
Nitrogen	1·0	1·0	1·0	0·97	0·9	0·88	0·8	0·55
CO_2 ..	0·9	0·85	0·8	0·8	0·8	0·8	0·8	—
Air ..	1·0	1·0	1·0	1·0	1·0	1·0	1·0	1·0
CHF_2Cl	1·4	1·35	—	—	—	—	—	—
CF_3Cl..	1·65	1·65	1·7	1·65	1·55	1·45	1·45	—
CCl_2F_2	2·7	—	—	—	—	—	—	—
SF_6 ..	2·7	2·5	2·3	2·2	2·2	—	—	—

The equality of strength between air and nitrogen was found by Skilling and Brenner[12] to persist up to a pressure of 20 atmospheres for a gap length of approximately 1 mm using an alternating voltage supply.

There are several general conclusions which can be drawn from these comparisons.

There is still a need for the repetition of these tests to provide confirmation of the present results. In almost every other case there are important differences in the way of carrying out the experiments which make comparison difficult. Only for air—and then in only two previous experiments, those of Howell[10] and Boulloud[26]—can comparison be made with confidence. In these cases the agreement is within the likely experimental accuracy on both sides, the degree of scatter of the results is small and the curves can be reproduced without difficulty. Within the limits described in the previous Section it is submitted that a similar confidence can be placed in the remainder of the present results.

No general value can be placed upon breakdown tests on commercial nitrogen at high pressures. From a fundamental point of view, ignorance of the impurity content and inability to control it makes analysis of the results impossible, and from the practical side there can be no reliance on the actual figures for breakdown strength. For the reason stated in Section 3.1 it is not certain that the present results can be accepted as giving the breakdown strength of pure nitrogen.

Apart from the differences in experimental procedure which are a likely cause of the variation in the relative electric strengths of the gases shown in Table 6, the impurities in the gases are not usually stated and may have a significant influence on the breakdown potential. Foord[25] reported, and later tests in this laboratory have confirmed, that relatively large variations occur in the breakdown-potential/pressure characteristics for the positive point-to-plane configuration in the halogenated gases, for repeat tests under the same condition. In particular, the pressure and voltage at which the maximum in this characteristic occurs are uncertain. For this reason, Foord[25] suggests that the phenomena observed under these conditions are critically dependent on gaseous impurities.

The Arcton 4 and Arcton 6 used in the present experiments were made to the following specification:

High-boiling-point impurities: not greater than 0·05% by volume.
Non-condensable gases: not greater than 5% by volume in the vapour phase.
Water: not more than 0·005% by weight.

Arcton 3 impurities are believed to be of the same order.

The impurities of the sulphur hexafluoride used were

Water: less than 25 p.p.m.
Disulphurdecafluoride: less than 50 p.p.m.
Readily hydrolysable lower fluorides of sulphur expressed as SF_4: less than 100 p.p.m.

Whilst nitrogen may be more sensitive to impurities than the halogenated gases, for breakdown in the uniform field gap, these figures advise caution in the interpretation of the results.

The suggestion that the reduction in the increase in the spark/breakdown voltage at high gas pressures was due to the pulling out of electrons from the electrodes was made by Ryan[27] in 1911. The cathode surface-work function, and therefore presumably the cathode material, should, on this account, be important in the breakdown process. A dependence of the spark-breakdown voltage upon the electrode material has been reported by Skilling,[28] Young,[29] Trump, Cloud, Mann and Hanson,[15] Boulloud[30,31] and Bright.[32] The present work confirms this general observation and also that the anode plays a part in the breakdown process (see Reference 15). However it is concluded that the presence of oxide layers on the surface of the electrodes has more influence upon the spark-breakdown potential than the type of electrode metal used. Section 4.3 discusses this matter further.

The smooth increase of breakdown strength with density, reported for carbon dioxide by Young[29] for the transition from gas to liquid phases, was not reproduced in the present experiments. However Young does not give measurements taken in the liquid itself. Zeier[14] observed bubbles when measuring the breakdown strength of liquid carbon dioxide and concluded that such breakdowns were taking place in a gaseous medium. In so far as it was possible at times, after conditioning by sparking in the liquid, to obtain breakdown potentials as high as those obtained in the saturated vapour, the liquid can be considered technically pure and the breakdowns can be explained on the gas-bubble theory. On the other hand, the frequent lowering of the breakdown potential below that characteristic of the saturated vapour when the gap was immersed in liquid must be ascribed to the introduction of impurities brought in with the liquid. The breakdown then occurs by the formation of a bridge of impurities (particles) across the gap.

(4.2) The Failure of Paschen's Law

Paschen's law states that the sparking potential is a function of the product of the gas pressure and the gap length. If, therefore, the sparking potential is plotted against the gas pressure for constant values of the parameter pd (pressure × gap-length) the law will be obeyed if a series of horizontal straight lines results. Any inclination of these lines to the horizontal will be a measure of the failure of Paschen's law. Such lines are shown in Figs. 4 and 5 for nitrogen and air respectively.

There is evidence that the law is obeyed, within the experimental accuracy, up to a pressure between 15 and 20 atmospheres. As the pressure increases further the deviations become greater, but there is no suggestion of any but a gradual change, in the range studied.

The breakdown potential of air is directly proportional to the gap length (Fig. 19). If Paschen's law obtains we have, at once, that the breakdown potential V_s is directly proportional to the gas pressure and also that

$$V_s = \text{constant} \times \text{p.d.}$$

This gives the familiar straight-line portion of the Paschen curve. In such a case E_s/p will remain constant as p varies ($E_s = V_s/d$).

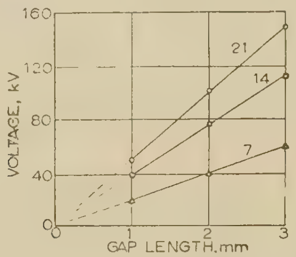

Fig. 19.—The variation of the spark-breakdown strength of air with gap length.

Electrode material: bright mild steel.
The numbers give the gas pressure in atmospheres absolute.

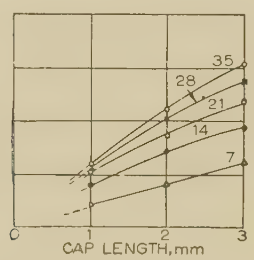

Fig. 20.—The variation of the spark-breakdown strength of nitrogen with gap length.

Electrode material: bright mild steel.
The numbers give the gas pressure in atmospheres absolute.

It has been established that α/p is a function of E/p for air and nitrogen and other gases. The experimental verification of this by Sanders[33,34] and Posin[35] for air and nitrogen respectively has covered a range of E/p from 20 to over 100 (volts/cm/mm Hg).

If the constant value of E_s/p lies within this range there is a corresponding constant value of α/p which we may call α_s/p. Now the experiments of Sanders and Posin were performed at pressures below atmospheric, and it is assumed that these results apply for similar values of E/p when both E and p are greater by a large factor. A certain value of E/p implies that a certain energy will be imparted to an electron as it is accelerated by the field over the distance of a mean free path. It is not to be expected that the mean free path will vary with the density, except in inverse proportion, until the critical pressure is approached, and the assumption is therefore considered reasonable.

A constant value of E/p implies a linear variation of α with p.

The variations of α_s with p for air and nitrogen are shown in Fig. 22. The figure was obtained by first plotting the variation of E_s/p with p as shown in Fig. 21. It is seen that for nitrogen, E_s/p is within the range for which α/p has been measured, for pressures up to 33 atmospheres. For air, corresponding values of α/p are available for the entire range of E_s/p. The figures for α/p given by Sanders[33,34] and Posin[35] in the range for E/p between 20 and 43·5 were used to enable a final plot of α_s against p to be made.

Considering Fig. 22, it should be pointed out that in the

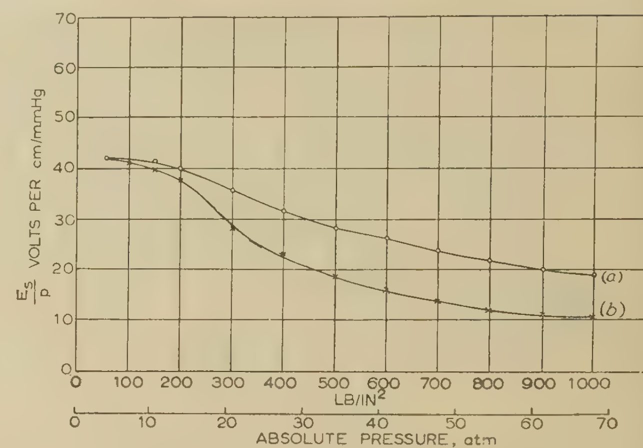

Fig. 21.—The variation of E_s/p with pressure.

Electrode material: bright mild steel; gap length G, 1 mm.
(*a*) Air.
(*b*) Nitrogen.
X_s—Applied field gradient at breakdown.

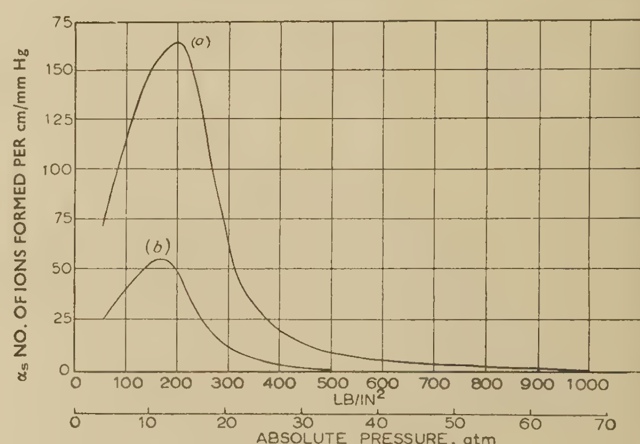

Fig. 22.—The variation of α_s with pressure.

Electrode material: bright mild steel; gap length G, 1 mm.
(*a*) Air.
(*b*) Nitrogen.

α_s—Value of the first Townsend ionization coefficient, α, corresponding to the spark-breakdown voltage.

pressure range where α_s is changing fairly rapidly, the values are very sensitive to the magnitude of E_s/p. Owing to the scatter in the results, the value of α_s plotted may be in error by 25%. However, because the figures used for calculating the values were taken from a smooth curve of V_s against p, it is considered that the general trends in the changes of α at breakdown are shown faithfully.

Up to a pressure of 10 atmospheres it is seen that the curves approximate to that linear variation of α with p anticipated above.

Fig. 20 shows that the linearity of the breakdown-potential/gap-length characteristics applies for nitrogen at 7 atmospheres but not at 14 atmospheres. For air (Fig. 19) the characteristic with the parameter of 21 atmospheres may depart slightly from linearity, and Howell[10] shows decided curvature for these gap lengths at 40 atmospheres. It seems possible to conclude that, where a linear relationship between the breakdown potential and the gap length may be demonstrated and where Paschen's law also holds, a linear increase in the value of α_s, due to the applied breakdown field, occurs as the gas pressure is increased. New information about the limits determining the validity of the law is not presented here. In the pressure region

where failure of the law might have been shown from the loss of linearity in the variation of the breakdown voltage, there is a similar loss of linearity in the variation of V_s with gap length. Above 20 atmospheres pressure for air and 10 atmospheres pressure for nitrogen, Paschen's law fails increasingly, but more detailed analysis of its failure is not possible along these lines.

(4.3) The Criterion of Spark Breakdown at High Gas Pressures and the Electric Strength of Different Gases

Above a pressure of about 13 atmospheres in a 1 mm gap, the data of Fig. 22 indicate a marked change in the relationship between α_s and the gas pressure. The measurements of ionization and attachment coefficients in electronegative gases by Harrison and Geballe[36] have shown the importance of considering both these phenomena in the interpretation of the measurements of pre-breakdown current growth in uniform field gaps. Especially in the case of air, α_s is more properly defined as the effective number of new electrons created by one electron moving 1 cm in the direction of the applied field.

Above 20 atmospheres for nitrogen and 33 atmospheres for air, the electron avalanche, which dominates the theories of breakdown of small gaps at lower pressures, has become of tiny proportions. Boulloud[26] from similar considerations, and Young,[29] from measurements of pre-breakdown currents in carbon dioxide, also comment on the decreasing probability of impact ionization before breakdown as the gas pressure increases. The propagation of a positive retrograde streamer according to the well-known description by Loeb would not appear to govern the criterion of spark formation under these conditions.

Although the Townsend α coefficient dominates the mathematical criterion for spark breakdown derived from the Townsend current equation, the first departures from Paschen's law which occur as the gas pressure increases have been explained by Llewellyn Jones and Morgan[37] on the Townsend theory. They discuss the dependence of the secondary coefficient upon the field gradient, E, rather than upon E/p.

However, an additional experimental fact has to be considered at this point. At these high gas pressures the breakdown field gradient is of the order 0·5 MV/cm, and it is at such field strengths that Llewellyn Jones and his colleagues[38,39,40] have shown that there is a current emission from the oxide coating on a metallic cathode which follows the general field emission law. As the field across the gap approaches the breakdown value, a stream of electrons will be drawn from the cathode and will be accelerated across the gap by the field. The growth of this current is very rapid as E increases [$i = AE^2\varepsilon^{(-D/X)}$ where A and D are constants (Reference 39)]. It is plain that this phenomenon must be included in the criterion for spark breakdown at high gas pressure.

If, in fact, field emission becomes the dominant pre-breakdown phenomenon in the high-pressure spark gap, the breakdown voltage should become independent of pressure. This condition is approached in the nitrogen (oxygen free) used between 35 and 70 atmospheres pressure (Fig. 4).

To fix ideas about this new criterion for spark breakdown we may adopt the fundamental idea of breakdown studies that the criterion defines a certain value of pre-breakdown current which must be established in the gap before breakdown occurs. The new criterion is then seen to be concerned with (*a*) the emission characteristics of the cathode, (*b*) the density of electronegative molecules in the gap, and (*c*) the probability of electron attachment to these molecules.

The reasons for the different electric strengths of different gases have been sought primarily in terms of their effective ionization coefficients. Hochberg and Sandberg[17,18] have sought an answer in terms of the differences in the effective α coefficient. Craggs[22,41–43] and his colleagues have shown a partial explanation in terms of the varying importance of different types of collision between electrons and gas molecules. Camilli and Plump[44] have given a comprehensive review of this question within a general discussion of fluorine-containing gaseous dielectrics.

The present work emphasizes the fact that, under conditions of high applied-field, electron multiplication in the gas becomes of less importance in the breakdown criterion, and the electron-emission properties of the cathode have to be considered as well as electron capture in the gas.

It would be expected that the effect of a fixed number of electronegative atoms or molecules in a gas gap would be gradually swamped as the breakdown field increased with increased gas pressure and the pre-breakdown electron emission from the cathode increased. Thus on this picture, at sufficiently high gas pressure, the spark-breakdown voltage of the mixture curves of Fig. 7, for example, should become independent of the gas pressure, as is the case with nitrogen (oxygen free).

The difference between the effect of adding air (oxygen) to nitrogen and the effect of adding carbon dioxide to nitrogen (Figs. 7 and 8) thus finds a qualitative explanation in terms of the superior electron affinity of the oxygen molecule.

(5) ACKNOWLEDGMENTS

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DISCUSSION ON

"THE ELECTRIFICATION OF THE MANCHESTER–SHEFFIELD–WATH LINES, EASTERN AND LONDON MIDLAND REGIONS, BRITISH RAILWAYS"*

Before a Joint Meeting of the LIVERPOOL ENGINEERING SOCIETY *and the* MERSEY AND NORTH WALES CENTRE *at* LIVERPOOL 21*st February, the* NORTH-EASTERN CENTRE *at* NEWCASTLE UPON TYNE 28*th February, and the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH 5*th April*, 1955.

Mr. G. A. Wallace (*at Liverpool*): I wish to refer to the overhead equipment for the tracks, which is briefly described in the paper. The authors point out that the equipment used is based on designs and practice evolved quite a number of years ago. The result has been that this overhead equipment has proved somewhat expensive. In the paper a figure of £6¾ million is given for the electrical engineering work, and I believe that something like £3 million of this represents the cost of the overhead equipment.

This being the case the authors rightly refer to the possibility of achieving economies, and mention five modified forms of construction which are being tried out, one of which is the use of tubular steel structures. I agree that these structures show savings of 40–50% in weight, but their higher fabrication costs will reduce the total net savings to about 25–35%, even when account is taken of reduced painting and erection costs.

These economies are obtained with welded tubular structures, which cannot be galvanized owing to the danger of explosion in the spelter bath, but they will not be achieved with bolted or riveted tubular structures. Therefore it seems likely that tubular structures would have to be painted. Recently, however, the cost of galvanizing structures has fallen to such an extent that it is now below the cost of satisfactorily cleaning and painting, so that this aspect of tubular construction will require careful consideration.

One interesting development, which is not mentioned in the paper, concerns an economical method of wiring siding tracks which was tried out in the Ashton Moss Sidings. Here the normal sidings equipment of about $0 \cdot 36\,\text{in}^2$ is spliced in mid-span into two smaller equipments of about $0 \cdot 21\,\text{in}^2$, and these two smaller equipments are then used to wire two tracks. This method is going to be used on the Shenfield–Chelmsford–Southend scheme, now under construction, and shows considerable economy, not only in copper but also in the cost of anchor structures required to terminate the equipments.

Under the heading of "Future Design Trends" the authors refer to a number of economies. It is interesting to note that the specification for Shenfield–Chelmsford–Southend incorporates all these economies except that relating to structures. Whilst increased design stresses have been permitted for structures, the minimum thickness of steel has been increased from 0·3 in to 0·35 in, despite the fact that the structures will be galvanized and used in a cleaner atmosphere than that on the Manchester–Sheffield scheme. This seems to be an unfortunate step and I should be glad to have the authors' comments.

The British Transport Commission's 15-year plan, involving electrification of about 3 750 track miles of railways, is a most welcome start on large-scale electrification. I should be glad to have the authors' views as to whether the equipment to be used will generally follow that outlined in Section 10 and now being used for the Shenfield–Chelmsford–Southend scheme.

High-voltage single-phase a.c. 50 c/s equipment is becoming increasingly popular in other countries, and the French appear to be standardizing on low-voltage d.c. equipment in the western half of their country with high-voltage a.c. equipment in the eastern half. I should imagine, however, that on a railway system as dense as that in Great Britain the problems of inter-running, with two different overhead systems and the old third-rail system, would be quite considerable.

Mr. W. Holttum (*at Liverpool*): The chief value of a paper such as this is its help in determining the designs to be employed for future work. The paper is a valuable record of what has been done on this electrified route, but I feel that two or three comments to explain why a particular alternative has been adopted should add considerably to its value. Two points in this respect are that the rectifiers used are stated to be continuously pumped on the recommendation of the contractor concerned, whereas, in Mr. Swift's paper on the Liverpool Street–Shenfield electrification, it is stated that pumpless rectifiers were used, and it was indicated there and in the discussion that these had been well established for a number of years, and they are of course more economical in both cost and space. The other point is in regard to the locomotives, of which there are two types, one having the buffing and draw gear mounted on the bogie, and the other on the under structure. It would appear that the buffing should be on the heavier of the two members in order to keep down the load on the attachment between the bogies and the body, but, rather surprisingly, it is the locomotive with the heavier bogies which has the attachments to the under structure.

It is stated that several alternative designs of overlap span were being tried, but the form of overlap used is not given. The desirable features of an overlap span appear to be that it keeps any extra copper to a minimum and balances the tensions so far as possible in order to keep down structure weight. The balanced overlap used on the Liverpool-Street–Shenfield electrification appears to meet these requirements very well.

In Section 8.2 it is stated that some trouble has occurred in cable joints owing to mechanical stress, and I would ask if this was caused by expansion or by subsidence.

Regarding the types of cable and methods of installation for future work referred to in Section 10, I would ask whether the departure from solid-type 33 kV cables is for economy or other reasons, and I should like to know whether the intention to use concrete ducts or asbestos cement pipes is related to the statement in Mr. Cock's paper† that there had been sheath failures arising from flexing at supports due to cyclic expansion and contraction. If so, recent investigation indicates that such sheath failure can definitely be avoided by suitably modified construction, so that the greater economy of erection in hooks on posts can be regarded as available.

Mr. H. M. Rostron (*at Liverpool*): There are three features of this electrification on which I would comment.

(*a*) *The time that elapsed before final arrangements were made to go ahead, i.e.* 1926–1938.—I suppose it is really unfair to criticize the apparent dilatoriness of the directors of the old railway

* BROUGHALL, J. A., and COOK, K. J.: Paper No. 1744, November, 1954 (see 102 A, p. 159).

† COCK, C. M.: "Electric Traction on the Southern Railway," *Journal I.E.E.*, 1948, 95, Part II, p. 115.

company in comparison with the go-ahead policy of their colleagues on the Southern Railway, but doubtless this was inevitable in view of the entirely different conditions, the incidence of the 1939–45 War, and in particular owing to the very severe nature of the route.

(*b*) *The unusually large number of signals required to control the traffic.*—This is explained by the authors as due to the complexity of the lines, but it must of necessity create difficulties in the future owing to maintenance problems caused by multiplicity of circuits and equipment and the exposed nature of the route. In this respect, I note in Section 8.3, that severe trouble is experienced with slipping, partly caused by metallic dust from the cast-iron brake-blocks. Since this metallic dust is also bound to affect adversely the various block sections of the track circuits for the colour light signalling, it would be interesting to know whether the authorities have carried out sufficiently exhaustive tests with moulded fabric brake-blocks.

(*c*) *The very high cost of this scheme.*—This is no doubt largely due to the complexity of the trackwork and terrain, and it cannot bear comparison with that of normal surface suburban or main-line change over. It is most gratifying to learn from the Press that the British Transport Commission and the Government appear to have accepted this view, in advocating the extensive plans for main-line electrification so recently made public. However, if the expected return on the original estimated cost of £3 000 000 was only 4·4%, it would be interesting to hear what return is expected on the actual cost.

From a long-term point of view, it appears that the nation must eventually make the greatest possible use of electric traction, and, moreover, adopt some form of electrically propelled vehicle for surface, elevated or underground passenger transport for all its great cities in order to circumvent the undoubted world shortage of liquid fuel, in addition to coal, which will occur in the foreseeable future. In fact, there is everything to gain by adoption in large cities of an integrated system of underground, elevated and surface public service vehicles, and the greatly extended electrification of railways, in order to reduce the congestion on the overcrowded roads of the British Isles. The chief problem here will be the economic integration of national prosperity, availability of labour and vital export need.

Mr. J. E. Macfarlane (*at Liverpool*): With regard to the overhead structure, can the authors say whether the conductor suspension is laid out to a true catenary, or whether it is considered sufficiently accurate to work to a parabolic curve?

Mr. P. d'E. Stowell (*at Liverpool*): The part of the paper that interests me most is that dealing with the supply arrangements. Section 4.3.2 dealing with the 33 kV switchgear is interesting in its reference to the economy which was introduced since 1951 by the use of so-called power-operated isolators in a manner not unlike that adopted in many cases by Manweb. Appendix 13.1.2 indicates that these devices have a short-time rating of 13 kA for up to five seconds, as indeed should be the case whether they are power-operated or not. It is not stated, however, whether they have a rated making capacity or breaking capacity which they definitely appear to need. Are they in fact power-operated switches as defined in document CV(ELE)1021 prepared as a draft British Standard* for oil switches?

In respect of this economy, it is unfortunate that, although Fig. 3 has a caption showing distinctive symbols for circuit-breakers, ordinary isolators and the so-called power-operated isolators, the diagram does not, in fact, have the appropriate symbols in the right places to be in accordance with the usage of the different devices as scheduled in Table 3.

In Section 4.3.4, one cannot help feeling that the provision of rectifiers has been on a somewhat lavish scale. I say this because Table 3 shows that the total rectifier capacity is rated at 47·5 MW, whereas Table 2 shows that the total estimated half-hour demand is 16·5 MW. This is a ratio of nearly 3 : 1. By comparison, the Wirral railway has 3·6 MW of rectifier capacity and a maximum demand of 2·3 MW—a ratio of only 1·6 : 1. Certainly the Wirral line is about the bare minimum, but it was intended to be, and it works successfully.

Quite apart from the aggregate rating of the rectifiers, I observe that it was considered that under the most arduous service conditions each rectifier would be required to be capable of four times the rated load, i.e. 10 MW, for 20 sec and three times the rated load, i.e. 7·5 MW, for 60 sec. According to my recollections three times rated load for 10 sec used to be the L.M.S. Specification for rectifiers for suburban services, and I was never able to obtain evidence that momentary loads in excess of 2½ times the half-hour demand on a rectifier ever occurred in practice, although I agree that it is easy to postulate conditions which in theory would produce higher ratios. Moreover, I would expect a main-line electrification of the type under consideration to result in a much steadier load, i.e. a lower ratio of peak to mean load than for a suburban service, since the accelerating time is a much lower proportion of the total running time for main-line trains.

To some extent there is a vicious circle: I say this because, if the capacity of individual rectifiers is more than it need be, the voltage drop at a given load is reduced and consequently the effective resistance of the rectifier is small by comparison with the resistance of the contact line, etc., between substations. As a result, the current taken by a particular train moving along the track is not so well shared through the paralleled d.c. connections between several substations. The outcome is that peak loads on individual substations tend to increase and still larger rectifiers become necessary. For similar reasons it can be a bad thing to install two rectifiers in the same substation except perhaps in special cases, e.g. at junctions, and consequently I doubt the wisdom of the alternate double- and single-unit substations which are rather characteristic of this scheme. It would be interesting to know whether it is certain that an installation of the same number of rectifiers more equally spaced, but with a normal rating of 1·5 MW each and a 10 sec rating of three times this value, i.e. 4·5 MW, would not have been adequate. Even this would provide an aggregate rating of 1·7 times the expected maximum demand. Indeed, instead of installing eight extra rectifiers at substations containing more than one rectifier, they would, I suggest, have been much better installed at eight of the eleven track section cabins. This would have involved no additional cost for d.c. switchgear, and with the economical high-voltage a.c. switching arrangement at all substations there would have been very little, if any, extra cost on that account to be set against a considerable saving from the use of smaller rectifiers.

I am very interested to see from Section 5.1.2 that on the $B_0 + B_0$ locomotives the tractive effort on the leading motor of each bogie has been reduced by field shunting to compensate for the weight transfer and reduce wheel slip. It is not clear whether the same applies to the C_0–C_0 locomotives, and I should like to know whether this is now common practice on electric locomotives—and is it also adopted on multiple-unit motor coaches? If the maximum possible tractive effort is required it is, of course, essential that the torque on each axle should not exceed the adhesion limit determined by the weight on the axle, but it seems a pity to have to discard available motor torque by field shunting. It is impossible to achieve the required equalization mechanically, and what is the amount of the weight transfer as a percentage of the tractive effort on the $B_0 + B_0$ locomotives, and what is it—presumably somewhat less—on the C_0–C_0 locomotives?

* The Document CV(ELE)1021 has now been published as B.S. 2631: 1955.

In the same Section there is a statement that automatic speed control is impracticable owing to variation in composition and type of train. Does this statement mean what it says, or does it mean that automatic acceleration control, as is normally provided on multiple-unit stock, is impracticable? The latter, I believe, is also not provided on these locomotives. If it means automatic speed control as I would understand it, I could perhaps accept the statement. But if it means automatic acceleration control, I am at a loss to understand why a driver watching an ammeter can do any better than, or even as well as, the usual current-measuring relay. On almost all the few starts made on a run from Guide Bridge to Penistone in July, 1954, when I had the privilege of riding in the cab of a $B_0 + B_0$ locomotive with a passenger train, the driver seemed to have great difficulty in deciding when to notch up, and I recollect that he had at least one axle spinning at some time during each start and the road did not appear to be unduly slippery.

In Section 10, on future design trends, the statement that so far as possible the tendency would be to take local supplies at 11 kV at each substation to avoid costly railway-owned high-voltage feeders is very interesting. But, in my judgment, there would be few substation locations at which it would be possible for an Electricity Board, say Manweb, to provide from an existing 11 kV system a supply capacity of 2·5 MW on a half-hour demand basis with peaks up to 10 MW. I therefore consider that transmission to such substations would have to be at 33 kV, and if the substations are located at 5-mile intervals it is difficult to see that there would be any cheaper method in general than running 33 kV transmission from one substation to the next roughly parallel with the railway. It is true that along some routes, e.g. Crewe to Runcorn, a 33 kV line exists broadly on this basis, but this must be the exception rather than the rule. It might be said that even from Chester all the way to Holyhead there are existing 33 kV circuits following the railway, but they have an average spacing of 3–4 miles. These circuits could not, however, be used as they stand since full use is already made of them, and extensive reinforcement would consequently be necessary which, in the event, would probably be equivalent to an additional circuit parallel to and close to the railway.

Broadly, therefore, I think that the cost of a railway supply would not be very much different whether it is provided and owned by the Railway or the Electricity Board. In some respects it may well be to the advantage of the Electricity Board to own the transmission system in so far as it might be co-ordinated with other local supplies, although the rapidly fluctuating nature of the railway load and the harmonic currents from the rectifiers are features that would need to be taken into account.

On the other hand, the railways have an almost ideal route for running a transmission circuit that is level, reasonably straight and with few wayleave difficulties. Indeed, one might almost say that something towards the supports for an open-wire line will exist, and I cannot help wondering why on the Manchester–Sheffield line, the 33 kV transmission was not installed as an open wire line on an extension to one of the stanchions supporting the overhead track equipment. Is the reason concerned with induction to open-wire railway signalling and telephone circuits? Or did these mainly have to be cabled to get them out of the way of the overhead structures? In any case, the effect should not be nearly so serious as that from a railway using single-phase 50 c/s alternating current for traction as is now coming into use, e.g. on the Lancaster–Morecambe–Heysham line and in France. I would be glad to have the authors' further comments on the use of power transmission by overhead 33 kV circuits carried on the structures, as is common practice in the United States and elsewhere abroad.

Three final questions arise on future design trends. First, what are the reasons for choosing oil-filled—I assume it means oil-pressure—33 kV cable in future? Secondly, has the p.v.c. serving anything to do with electrolytic corrosion from stray traction current? Thirdly, is the proposed abandonment of outdoor switchgear in favour of indoor compound-filled metalclad gear consequential on the switchgear being used for 11 kV as the result of the other proposal to take supply at this voltage, or would it apply equally if 33 kV switchgear continued to be necessary, and if so, why?

Mr. A. S. Robertson (*at Liverpool*): I should like to ask whether the authors have in fact been fair to the now obsolete steam locomotive in this particular section. On the Wentworth Bank four steam locomotives were required to handle 1 074 tons, where now two electric locomotives handle 850 tons. Assuming that the adhesive weight of the steam locomotive is about 65 tons, it seems that the electric locomotive is hauling 20% more than the steam locomotive per ton of adhesive weight.

This contrasts with a recent statement made by Mr. Nouvion that on the S.N.C.F. as a result of service experience it has been found necessary in the case of the B_0–B_0 type d.c. electric locomotive to take a coefficient of adhesion only three-quarters of that which is accepted for the steam locomotive.

Restarting on the ruling grade with the electric locomotive with the stated loads would appear to require about 25% adhesion, whereas it appears that adhesion drops as low as 17%. Can the stated loads in fact be handled with reliability or do they have to be reduced under poor rail conditions?

Difficulties have been experienced with negative pressure set up on the locomotive superstructure due to the traction-motor blowers. It is recognized as normal practice to keep the input side of the blowers and their associated filters separate, either by ducting or by a settling chamber, and thus to keep the locomotive equipment above atmospheric pressure. It seems that such an arrangement could with advantage be applied to this locomotive.

Mr. H. W. H. Richards (*communicated*): I should like to make brief observations on three matters, namely electrification system, energy consumption and high-speed locomotive.

As regards system, I will mention only two major points which influenced the recommendation in the First Report on this Scheme in 1926 and subsequent Reports up to 1944. First, it is not always appreciated by some people who write in the Press that the physical and traffic conditions relating to railways, and also roads, in this relatively small and densely-populated country vary in many respects from those in America, and in most European and other countries. Hence the difficulty hitherto, for instance, in finding suitable employment for Diesel-electric traction in this country, except in certain special cases, owing to our special traffic conditions and a smaller loading gauge, which has limited engine size.

According to Ministry of Transport returns, the average distance between railway stations is about 2½ miles, and junctions are relatively close together. There should therefore be considerable scope for multiple-unit trains with their convenient and economical features for train working. 1 500-volt traction equipments are considered quite suitable both for locomotives and for multiple-unit trains, and they are relatively simple in design and robust in construction, and hence cheap to maintain—a most important factor when a long working life is required.

Secondly, the use of an overhead-current-collector system means that the respective functions of current collection and running track can be separately cared for to the best advantage of both. This is again helpful both to operating conditions and to maintenance costs. Further, the distance between junctions in many areas in this country is small, and railway geography largely dictates the position of substations. Consequently the

distribution losses on the overhead line should be low—another useful factor in running cost.

As one who was responsible for the 6 600-volt a.c. overhead system on the old Brighton Railway suburban system for many years, I feel that higher alternating voltages could probably be used in this country without undue physical difficulty and costly alterations, but, owing to our atmospheric conditions, steelwork sections cannot be reduced below a certain limit, and therefore possible savings in first cost and maintenance costs are somewhat doubtful and might be more than offset on the rolling-stock side.

Whatever new proposals may be considered in the future, it is suggested that very careful consideration should be given to train-operating conditions in this country and to the total train-operating costs.

As regards energy consumption, this may represent not less than 16% of main-line and 30% of suburban train-operating costs. To check the original calculated consumption, special tests were made in early days with a recording dynamometer car, and these agreed very closely with the calculated consumptions for various types of train.

When complete electric operation has had more time to get established, it would be interesting to know the figures for maximum demand and average watt-hours per ton-mile.

Investigation in pre-1939 days suggested a load factor of not less than 50%, with a maximum demand between 3.0 and 4.0 a.m., and negotiations with the three large supply undertakings showed that, in accordance with the terms of Section 12 of the 1926 Act, the average cost per high-voltage kilowatt-hour would have been 0·333d., but times have since changed.

As regards the high-speed locomotive, prior to 1939 it was proposed to build various experimental types of wheel formation. A visit to the United States in 1945 showed that good high-speed running was achieved by heavy high-power Diesel-electric locomotives in that country, and this was undoubtedly due to considerable interest in bogie design. With this and other collected experience, a recommendation was prepared in 1945 for an experimental 6-wheel type, and it is interesting to learn that seven 6-wheel double-bogie locomotives have now been constructed.

It is very satisfactory to have good reports of their running conditions since, again owing to relative simplicity in design, both first costs and maintenance costs should be favourable, and it certainly seems quite possible that this locomotive should be capable—as regards horse-power and capacity for speed variation—of dealing with nearly all the main-line passenger and freight trains in this country.

Finally, without in any way wishing to hold back possible future developments which may offer possible higher technical efficiencies, it is suggested that those concerned should bear in mind that, although many things are possible, some things are not always expedient in actual practice, since the management naturally appreciate reliability and low running costs more than high technical efficiency.

Mr. F. C. E. Smith (*at Newcastle upon Tyne*): The traffic density on the Manchester–Sheffield line of 4·7 million trailing ton-miles per annum per single-track mile is above the figure at which the 1951 committee estimated that electrification would pay. Allowing also for the difficult operating conditions with steam traction, there should be a good return on the capital expenditure in the savings effected in the annual charges with electric operation. If these results are realized they will prove the sound financial basis of the recently published intention of the British Transport Commission for further electrification including two of the main lines from London, both of which have traffic densities in excess of the Manchester–Sheffield line.

It is not clear whether the estimates of the capital costs allow any credit for the value of the steam assets released. The largest of these credits will be for steam locomotives, and it would therefore be interesting to know how many of these engines were released by the introduction of 65 electric locomotives and eight 3-coach multiple-unit trains included in the scheme.

Although it was originally intended to retain the open-wire telephone lines, it was subsequently decided to put all communication circuits into cable. It is not stated whether this was carried out as part of the normal communications betterment work, or whether it was done because it was found impracticable to immunize the open-wire lines against interference from the traction system.

Among future design trends it is suggested that double reduction gears may be used to reduce traction-motor weight. This drive can, of course, be applied only to low-speed locomotives. Allowance must be made for the cost of the more complicated gear-box, the increased gear losses and higher maintenance charges when assessing the price at which any saving in motor weight is achieved. Apart from the recent motor-generator locomotives of the S.N.C.F., which have a stop speed of only 37 m.p.h., the double-reduction-gear drive has been extensively used only in shunting locomotives, where the greatest advantage can be obtained from the high gear-ratio available.

Mr. H. F. Jarvis (*at Newcastle upon Tyne*): On the d.c. side it is noted that no provision is made for giving supply to the contact wire in the event of the failure of a high-speed circuit-breaker. This facility would also enable maintenance or repair work to be carried out at any time without the disadvantage of having to run the system with a single-ended feed.

It would be interesting to know why the facility was omitted from this scheme, although it was included in the Shenfield electrification, and whether the omission has caused any inconvenience in operation.

The high-speed d.c. circuit-breakers are arranged for forward tripping, the relationship between the line voltage and the tripping current following a falling characteristic. Do the authors consider that this is a desirable characteristic, and is it intended that this characteristic be incorporated if the circuit-breakers of the future are solenoid-operated from a power battery instead of from the 1 500-volt d.c. supply?

With regard to the supervisory control system, I note that future installations would probably be of a type giving direct control and indication of each switch from a miniature diagram instead of the common diagram system. Would the authors state what has prompted this change of policy and whether sufficient experience of the direct control system has been obtained to justify its use in the future?

A further point in this connection is the siting of the control room. Do not the authors consider that it would have been better to locate the control room close to the electric traction engineer for the area, so that closer supervision and personal expert guidance could be available in the event of wide disruption of the service?

Has there been any trouble due to ice forming on the contact wire, and what, if any, de-icing precautions are taken?

Reference is made in Section 5.1.2 to the incorporation of spring or rubber connections between the rim and centre of the gear wheel. Have the authors any further information regarding the relative performance of these two types of connection?

Finally, with regard to the multiple-unit stock, do the authors consider that the electro-pneumatically-operated door gear is justified, bearing in mind that the Southern Region has not adopted this feature on its new rolling stock?

Mr. A. T. Crawford (*at Newcastle upon Tyne*): It was interesting to hear Mr. Cook's reference to the special training which is

necessary for the existing operating personnel who have been trained on steam working, to adapt them for their new duties on electric locomotives. The preparation and supply of the comprehensive manuals which Mr. Cook mentioned seems most useful, and there is a growing tendency these days with power-station staff, for example, to provide them with adequate literature describing the plant which they have to operate, and giving them adequate training, prior to the commissioning of the station, on the type of plant being installed. In view of the much more extensive programme which is envisaged for the future, could the authors indicate how they propose to arrange such training and the length of time the operators should spend on such a course. Presumably the training period would include some instruction at a works during the assembly and testing of locomotives.

Mr. O. L. Robson (*at Edinburgh*): In Section 4.3.4 the authors give brief details of the rating of the rectifier equipments. This is given as 2·5 MW (nominal), which is the r.m.s. value of the specified load cycle. In the case of the rectifier transformers, this nominal rating is a reasonable assessment of the size of the unit, but in the case of the rectifiers, the r.m.s. value has very little meaning, since the maximum loading has a far greater effect on the true size of the unit. In this connection it is interesting to make a comparison with the rating and size of the rectifiers on the Liverpool-Street–Shenfield line described in Mr. Swift's paper,[2] where the units are stated to be of 2·0 MW (nominal) rating, this figure again being the r.m.s. value of the specified load cycle.

On the Liverpool-Street–Shenfield line the 5 min overload is 150% of the nominal rating, while on the Manchester–Sheffield–Wath line it is 200%, and the maximum overload on the Liverpool-Street–Shenfield line is 300% of nominal for 10 sec, while on the Manchester–Sheffield–Wath line it is 400% nominal for 20 sec. Allowing for these considerably heavier overloads, I consider that the true size of the Manchester–Sheffield–Wath rectifiers is at least 75% and possibly 100% greater than that of the Liverpool-Street–Shenfield rectifiers.

In the last sentence of Section 4.3.4 the authors state that filter circuits are installed to reduce the 600, 900 and 1 200 c/s harmonics. With 12-phase rectification the 900 c/s harmonics are of only nominal value, and actually only two tuned filter circuits for 600 and 1 200 c/s are installed on this scheme.

Section 8 is limited to experience gained on the Wath Branch, since this was the only section of track on which operating experience had been gained at the time when the paper was submitted to The Institution in 1954. Since the paper is a record of the first main-line electrification scheme in this country, to which reference will no doubt be made for many years to come, I consider that it would be of considerable interest and value if the authors could give more extensive operating experience on the other sections of the scheme, like the information given in the booklet published by the British Transport Commission on the occasion of the official opening of the line.

As a result of two years' operating experience the authors list four slight sources of trouble, two of which are due to subsidence which had been anticipated and allowed for in the original engineering of the scheme. The reference to two failures of rectifiers due to leakage through the anode ignition seals is rather misleading, and I should like to give a little explanation of this particular trouble. It must be remembered that these rectifiers are of the continuously-evacuated type, so that a seal fault is of minor importance compared with a seal fault in a pumpless rectifier. The seals which gave the trouble were not the anode ignition seals but the small seals for the grid intakes. When manufacture was recommenced after the 1939–45 War, it was not possible to obtain the type of seal which was originally designed and extensively tested, and a substitute type had to be adopted in order that manufacture might proceed without delay. The two cases have occurred with the substitute type of seal. By the time the manufacture of the later air-cooled units was proceeding, the original type of seal was obtainable and was fitted to these later rectifiers. It is this type which has since been fitted to the rectifiers where the trouble occurred.

Section 10, on future design trends, is of particular interest in view of the modernization plan recently published by the British Transport Commission. The most intriguing sentence in this Section is that the rectifiers would be of the pumpless fan-cooled type in glass or steel containers unless other types superseded the current mercury-arc rectifier. So far as I am aware, the only development at present in hand with alternative types are the mechanical and germanium rectifiers. The former is not suitable for the voltages required for traction service, and I should like to know whether the authors consider the germanium rectifier to be sufficiently advanced in design and in operational experience for it to be considered for this modernization plan.

Mr. C. M. Beckett (*at Edinburgh*): Since this is an integrating paper, and will be referred to for many years by those interested in electric traction, I would ask that further facts be recorded.

What is the load factor—either overall or of each of the three supply points?

What are the average locomotive miles per year for each of the two classes?

Very approximately, what percentage of the traction load is regenerated current? I am aware that much of the value of regeneration is indeterminate, such as saving on brake blocks and wheel turning. One of its advantages, namely absence of brake-block dust, can hardly obtain where there is already so much coal dust on the track.

In Section 8 it is stated that trouble from icing of conductors has been negligible. It is, however, on the ascents, east and west of Woodhead tunnel, that climatic conditions are worst. Will the authors say what has been the experience there, and whether it has been necessary to run locomotives light in order to free the conductor from ice.

The authors have described the difficulties experienced through dust entering the locomotives, and the methods adopted to reduce these. The dust which enters the vacuum braking system is not taken from inside the locomotive but from underneath the vacuum-braked stock, and one would expect a great deal of coal dust to be drawn in. When Mr. H. H. Swift was engaged in the electrification of the Capetown suburban lines, there was very considerable trouble through exhausters seizing and snifting valves sticking, owing to dust entering the system. Have any similar troubles been experienced?

One or two places are mentioned in the text and the reader is tempted to look for these in Figs. 1 and 2 without success. The most important is Dewsnap Yard in Table 1, which is 5 miles from Manchester, near Guide Bridge. Another is the Wentworth Bank of 1 in 40, which might be shown on Fig. 2.

Mr. A. J. Lilburn (*at Edinburgh*): The authors state that "regeneration resistors are installed at four strategically placed substations, namely Strafford Crossing, Barnsley Junction, Gorton and Wharncliffe Wood." Three of these substations, however, are on the eastern side of the scheme and only one, i.e. Gorton, is on the western side. I should like to ask the authors whether this has proved a satisfactory arrangement and whether there have been any operating difficulties, especially in view of the fact that Gorton is very near the Manchester end of the line and some distance from the section of track with the maximum gradient?

Mr. G. W. Parkin also contributed to the discussion at Liverpool.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. J. A. Broughall and **K. J. Cook** (*in reply*): The reply is arranged to correspond to the Sections of the paper.

Electrification Schemes.—We greatly appreciate Mr. H. W. H. Richards's contribution which is a valuable addition to the history of this electrification.

In answer to Messrs. Rostron and Parkin, it is still too early to give useful financial results, and the scheme is in any case too small and isolated to be used as a yardstick for the economics of railway electrification.

We hope to give the fuller information about the performance of the line for which Mr. Robson asks in our reply to the discussions during the 1955–56 session. The normal load factor of the line as a whole is approximately 56%, but the monthly figure has been as high as 68%.

Substations and Track Sectioning Cabins.—In answer to Mr. Stowell, the isolators are used strictly as remotely controlled isolators and the making rating given is to enable them to act as such. They have not a specific making or breaking rating in terms of the British Standard mentioned. A rather generous rating for the rectifiers was stipulated since it was realized that, on freight service in this part of the country, a considerable amount of "bunching" of trains might occur under bad weather conditions.

In answer to Mr. Jarvis, no inconvenience has been experienced when relying on a single end-feed on the rare occasions when a high-speed circuit-breaker is out of service for maintenance. Our views on high-speed circuit-breakers are given in our reply to previous discussions.*

In answer to Mr. Robson, 900 c/s filters were installed in some substations where it was originally intended that the rectifiers would be of the 6-phase type. It is believed that it will shortly be possible to regard the germanium rectifier as a practicable alternative.

It would certainly, in principle, be possible to adopt the disposition of rectifiers proposed by Mr. Stowell, but the financial effect of doing so would now be difficult to ascertain, since, if this system were adopted, a different load cycle would be required.

In answer to Mr. Lilburn's question about the siting of regeneration resistors, the late decision not to extend the electrification to Manchester Central Station has led to an element of unbalance, but, in spite of this, satisfactory results have been obtained with the existing disposition of the resistor banks.

Overhead Line Equipment.—We are in general accord with Mr. Wallace's remarks, and serious consideration is being given to the stipulations that should be made about thickness of steel for future work.

In answer to Mr. Macfarlane, the significant features of the conductor suspension are established on the basis of a true catenary.

Rolling Stock.—In answer to Mr. Rostron, much experimentation has been carried out elsewhere with alternative material for brake blocks, but without success, either on locomotives or "generally" on power bogies. There appears at present to be no general alternative to cast-iron as a friction brake.

In answer to Mr. Stowell, slip due to weight transfer can occur on the C_0–C_0 locomotive but it is rare, and compensation by field shunting has not been employed. It would be possible to couple wheels mechanically but this arrangement is not generally favoured.

The compensation for weight transfer on the $B_0 + B_0$ locomotives increases the effective adhesion by about 8%. No provision for weight transfer is made on the motor-coach equipments. Control of acceleration is left to the driver because of the big diversity in the nature of trains to be handled in freight working.

In answer to Mr. Robertson, adhesion as low as 17% has been measured and difficulty in starting on severe gradients may then be encountered. Very rarely assistance may be required but, as stated, loads are handled satisfactorily in large numbers. Separate ducting on the input side of motor blowers would have certain advantages, but in conjunction with a settling chamber it would require too much space within the locomotive.

In answer to Mr. Smith, the number of steam locomotives released by this electrification is reckoned as 118. Since these locomotives are life-expired, credit is relatively small, but as renewal provision is made annually a considerable contribution to capital expenditure is available.

In answer to Mr. Jarvis, both types of flexible gear drive have given satisfaction. It is probable that the tendency on future electrification will be not to fit air-operated doors.

In answer to Mr. Crawford with regard to training, it is anticipated that future requirements will be met on lines broadly similar to those described. It is not felt necessary for operating staff to be trained in manufacturers' works. Technical contact during construction is, of course, maintained.

Experience of Wath Branch.—In answer to Mr. Holttum, the joint failures mentioned were small in number and were due to expansion rather than subsidence. We are obliged to Mr. Robson for the particulars he gives of the change in seals, with which we are in accord.

In answer to Mr. Smith, it is probably true that this open telephone wires were cabled on principle, but tests on a section of open-wire line have shown that this was also necessary to avoid interference.

In answer to Mr. Crawford, the average annual mileage since the inauguration of full operation has been:

$B_0 + B_0$: 44 000 miles
C_0–C_0: 68 500 miles

The short length of haul prohibits high annual mileages. Difficulties due to ingress of dust in the vacuum-brake system have not arisen, probably on account of the relative volumes of air. The majority of the freight trains are composed of unbraked stock, for the handling of which the air brake is used.

Future Design Trends.—We have explained our preference for oil-filled cables in the reply to the earlier discussion,* and in answer to Mr. Holttum, we would propose that these should be continuously supported. It is our view that when all circumstances are considered, a p.v.c. sheath would have advantages over a lead or lead-alloy sheath, but we have not specifically in mind avoiding troubles due to corrosion, mentioned by Mr. Stowell, from which these cables have been immune.

In answer to Mr. Stowell's proposition regarding the use of overhead 33 kV power-transmission circuits carried on structures, according to our information this is becoming increasingly infrequent.

In answer to Mr. Jarvis, the use of the direct-control-system miniature diagram, which is really a reversion to earlier practice, seems likely to be preferable on the larger systems with which we shall probably be concerned in the future.

We agree that apparently there would be difficulties in taking 11 kV supplies locally, and our recommendation in favour of indoor switchgear would apply equally to 11 or 33 kV type.

* See 1955, **102** A, p. 185.

DISCUSSION ON

"SOME DESIGN FEATURES OF THE SEMI-OUTDOOR POWER STATION AT INCE"*

Before the Southern Centre *at* Hove *10th February, the* Mersey and North Wales Centre *at* Liverpool *1st March, the* North-Eastern Centre *at* Newcastle upon Tyne *8th March, the* North-Western Supply Group *at* Manchester *13th April, the* South Midland Supply and Utilization Group *at* Birmingham *11th October, the* Western Supply Group *at* Bristol *8th November, and the* North Midland Centre *at* Leeds *7th December,* 1954, *and the* South-East Scotland Sub-Centre *at* Edinburgh *18th January,* 1955.

Mr. E. McCabe (*at Hove*): In Section 3.1 the author suggests "that the completed station must present an acceptable appearance." Fig. 6 suggests that there has been a change of heart on the part of certain bodies who apparently wield considerable authority, and who, until quite recently, seem to have held the view that the sight of an inclined conveyor gantry would be offensive to a hyper-sensitive public and that it was necessary to conceal precipitator casings, tanks, and draught plant behind screen walls which served no other useful purpose. It will be reassuring if the author can confirm that this change has taken place.

In Section 2.3 it is stated that pumping to settlement areas from which the top soil has been stripped, and then resoiling, proved impossible. Since there is so much to be said for this method of disposal from the operating aspect, and especially in view of projects at present going forward for which this method is intended, it would be of interest to know what obstacle stood in its way at Ince.

The cooling towers are completely exposed at the northern extremity of the site. I recollect a paradox arising at a station with which I was at one time associated; as a result of extremely cold weather the skirt of the cooling tower was blanketed with curtains of ice which interfered with air ingress to such an extent that it became necessary to reduce station load because insufficient cooling was available. Have any precautions been taken at Ince to ensure that this state of affairs cannot arise?

Finally, I deprecate the view apparently held by many people as a result of plant shortage that the building of a generating station is an end in itself. The obligation confronting the Central Authority and the Generating Divisions is to produce electrical energy, and the building of generating stations is merely a means to this end. I prefer to regard the paper as an introduction to a paper to be produced when the Ince station has been in commission for perhaps five years, which should include extensive reference to operating problems and results, and would perhaps enable the view to be expressed, not merely that "these are our ideas," but also that "these are good ideas."

Mr. A. J. Din (*at Hove*): I am uncertain whether the cladding at drum level was carried completely underneath in the form of a floor, or whether this area was left open; in the latter case considerable trouble might be experienced with gauge-glass failures and erratic functioning of the feed-water regulators, owing to extreme temperature changes.

The paper indicates that corrosion troubles are not expected to be worse than those met with on the more orthodox layouts, but it seems that air-heater corrosion might be excessive, particularly with coals having high sulphur contents, and I should be interested to know the class of coal it is intended to fire.

In common with modern practice, automatic soot-blowing will be normal procedure, but difficulties might be encountered should it be necessary to resort to manual operation during the winter months.

Mr. A. Abbott (*at Hove*): A power-station building ought not to be constructed to outlive by many years the installed plant. By careful design, fabricated structures and any exposed plant can be made to look quite neat. It seems foolish to house generator transformers in a costly brick-built annex when almost the same things are fully exposed in many Grid substations situated in or near good-class residential property.

I think we have gone too far with amenities; some power stations built since nationalization have blocks of offices with the dimensions of a medium-size cotton mill, with most expensive ablution devices, locker rooms and the like. A close check should be made on such expenditure, as it runs away with a great deal of money.

The author mentions a possible saving of £2 per kilowatt in economizing on civil-engineering costs. I think another £1 per kilowatt might be saved in simplifying the main and auxiliary switchgear layouts, which are too elaborate in many cases.

Mr. L. H. Fuller (*at Hove*): The author has not sufficiently stressed the great importance of saving of even £100 000 on the cost of a power-station building. The omission of even the curtain wall can save quite a lot of money, and a 2 yd length of a 10 ft-high wall costs almost as much as one electrical service. If the wall were 100 yd long and 30 ft high, the cost of over 200 services would be saved, and I feel sure that this would be welcome to many engineers.

No financial saving should be related to the total capital cost of the project. This relation is a point which is unfortunately often stressed at public inquiries into erection of lines or substations, but to my mind a saving or extra cost of £1 000 carries the same value whether the initial cost of the job is £10 000 or £100 000. The saving of a large sum on any project can be attained by the omission of one large feature or by saving on a multitude of small features.

Mr. S. R. Steinbock (*Colombia: communicated*): I feel that the policy adopted for Ince was far too conservative. The policy "that all main operation positions and parts of the plant requiring routine access for either operation or maintenance should be adequately protected . . ." has, probably more than anything else, hampered the designers and limited their scope. The present-day trend in industry as a whole is to minimize enclosures and to provide shelter either where operating personnel are continuously present, where weatherproofing the equipment itself would be so costly that enclosures would be justified or where temporary scaffolding and shelter for maintenance purposes would be so costly as to justify the installation of permanent enclosures. For routine access or minor maintenance, permanent enclosures are not necessary, and almost every type of equipment can nowadays be furnished with weatherproof enclosures for outdoor operation.

Had a less-conservative approach been adopted, in all probability the layout would have been different. For example, was a study made of grouping the boilers in pairs, with coal bunkers back-to-back? Such an arrangement might have allowed sufficient room for covered control and turbine rooms, while the switchgear and station auxiliaries would, of course, be located out of doors. Alternatively, there could be sufficient room for the turbo-generators between the boilers and the precipitators, either in a back-to-back or in a single-line layout.

* Brown, F. H. S.: Paper No. 1589 S December 1953 (see 101, Part II, p. 103).

It is interesting to note the author's concern over station efficiency, but perhaps the emphasis should have been placed on seeking a more efficient cycle. British designers have made a gratifying progress in raising the thermal efficiency of the more recent plants. It is unfortunate, however, that the progress has been so pitifully small compared with that in the United States, and especially so considering Britain's coal position. Recent installations in the United States have a thermal rating of about 8 900 B.Th.U./kWh (i.e. an efficiency of 38%) and currently designs are being developed for plants operating at over 4 000 lb/in^2 with an indicated efficiency exceeding 50%. The use of pressures exceeding 2 000 lb/in^2 (since 1937), of units with a capacity exceeding 1 000 000 lb/hour and throttle and reheat temperatures exceeding 1 000°F has given the Americans a lead which British designers can ill afford to let pass unchallenged.

It is gratifying that a fresh approach has been made to power-station design in Britain, and one can only hope that the progress will continue unabated, so that once again the erstwhile position of leadership in this field will be restored to Britain.

Mr. P. d'E. Stowell (*at Liverpool*): The author claims that the gross reduction in capital cost due to the semi-outdoor design at Ince may be £1 per kilowatt installed as compared with an orthodox station, but he does not indicate the type of boiler-house construction used in the latter. It does not appear to me from the drawings that there can, in fact, be a great difference between the cost of this station and that of a corresponding station with the whole of the boiler-house enclosed in corrugated-iron sheeting, as distinct from brickwork. The author claims that there is a case for segregating each boiler from its neighbours to provide additional amenities for the maintenance staff, but in addition to electric heating which he is providing for frost prevention, he may also have to provide electric heating to keep the men warm while maintaining the cold boilers.

Comparing Ince with the station that I know best, namely Portobello, it seems to me that the latter might almost as much be called a semi-outdoor station as the former. The only additional items that are outdoors at Ince are the forced-draught fans, and if at Ince the boiler-house as a whole were enclosed, the two stations would not be very considerably different. I am also at some loss to understand why the author claims that the semi-outdoor design facilitates the pipe runs vertically downwards in the space between the front of the boiler and the bunkers, which is where they run at Portobello; surely this is a normal feature of any well-designed station.

Mr. W. H. C. Pilling (*at Liverpool*): Are American engineers still as enthusiastic about the semi-outdoor type of construction? I have heard that later experience in the United States has not been as satisfactory as anticipated.

In Section 3.2 the author notes that the ash-hopper floor is about 14 ft below ground level. Would he advocate this for a conventional station where foundation conditions are the same as, or similar to, those at Ince?

Do the foundation costs in Table 1 refer to all foundations on the site or only to those of the main buildings? I do not agree entirely with the author's statement that Ince is not an easy site so far as foundations are concerned. The foundations for the main buildings are constructed directly on load-bearing strata, and piling has been necessary only under the cooling towers and ancillary buildings and plant. No abnormal difficulties have been experienced.

In Section 3.5 the author refers to the rapidity of construction which this type of station encourages; I think it should be pointed out that we have been extremely fortunate in the weather conditions during the period of construction of the first boiler unit, and this has undoubtedly influenced the speed of construction. The other point I should like to emphasize is the importance of constructing the intermediate concrete floors around the boilers at a fairly early stage in the boiler erection period, because they then afford some degree of cover from the weather.

Although the author has referred to precautions to be taken against the effect of frost during outage of the boilers, it is hoped that the majority of heavy maintenance work will be done during the summer; we should endeavour to avoid prolonged outages during the three or four months when the worst of conditions are to be expected.

Mr. K. A. Hoadley (*at Liverpool*): When the paper was written there was some doubt about the treatment of the downcomers, so it may be of interest to indicate the final decision. We look at the problem under three headings: with the boiler working normally on load, with the boiler taken down for an outage of 3–4 days and then with the boiler down for a long period. Calculations showed that with the boiler taken off load on days with 20 degrees of frost and a 40 m.p.h. wind blowing, the downcomers would take 400 hours to reach freezing point with the water in the boiler; so we have decided that normally good standard lagging will be suitable for use at Ince and that the complications of electric heaters or warm currents of air, etc., need not be taken into consideration.

Another interesting point in the frost precautions concerns the feed-water regulators; each consists of three elements—the thermostat tube, the flowmatic element and the feed regulator valve; the position of these three items is fixed in space and there are linkages between them. It has been necessary, since the flowmatic element is outside the enclosure, to fix some small brick enclosures which are open to the warm air inside, so that the stationary static water in the diaphragm chamber does not freeze.

Mr. H. Bateman (*at Liverpool*): In Table 1 a comparison of civil-engineering costs is made between Ince and an orthodox station, but no mention is made of boiler costs. Is there not some increase in the cost of boiler plant in the semi-outdoor design which is not reflected in Table 1?

On the question of civil costs, if a departure is to be made from the orthodox design, is it not fair that a comparison should be made with other competitive methods and not merely a comparison of one unorthodox design with the orthodox? For example, the author mentions that further savings in capital cost could be made by abolishing the side enclosures between boilers, etc. If this principle were extended, using the same basic steelwork design, so that light cladding material enclosed the whole boiler-house, the savings in cost obtained would not be inconsiderable.

In this connection, it is interesting to note that the cladding area of the boiler-house walls could be reduced from about 67 000 ft^2 as at Ince to about 50 000 ft^2 for a completely enclosed building. This illustrates a point in the Ince design which to me seems fundamentally wrong, in that more cladding is used to house less plant. Subsidiary savings also accrue from the enclosed design in that open-mesh steel flooring would be used at drum and superheater levels instead of concrete, and weatherproofing of some exposed plant would not be required.

From the capital-cost aspect it seems that the justification of the Ince design is not at all clear and may, in fact, be dearer than the more enclosed (if not completely enclosed) station.

Does the author still consider, in the light of subsequent experience to date on Ince and other contemporary stations, that the optimum degree of enclosure has been obtained and that the subsidiary advantages, such as allowing maintenance to be carried out in a relatively cool atmosphere and the availability of more light during day-time, will compensate for the possible additional expenditure, loss in boiler efficiency and the inconvenience due to part of the station being exposed?

Mr. H. Tattersall (*at Liverpool*): Will the author comment on the desirability or otherwise of having the substation adjacent to the turbine house and the administration block sited elsewhere? It is essential, of course, that the control and relay rooms should be between the two, but these could be accommodated in a small building within the area of the substation.

What is the estimated saving in cost resulting from the connection of the generator transformers and 132kV switchgear by short lengths of open copper-work (rather than by 132kV cables as in the arrangement under discussion), and from the use of trunk multi-core cables both to the 132kV substation and the generating station, which might be achieved with the suggested alternative?

Mr. H. G. B. Mahon (*at Newcastle upon Tyne*): The additional cost of maintenance painting for the outdoor boiler-house is a factor which cannot be ignored. On the assumption that this is repainted every 5 years, as compared with, say, every 10 years in a modern orthodox station, the additional cost taken over 35 years' life of the buildings would be three times that of the maintenance painting in an orthodox design; the equivalent additional initial capital expenditure would be about 40% of this sum.

The author's claims in respect of earlier commencement of erection of the boilers on account of the lesser amount of structural steel which has to be erected in comparison with the orthodox station would, I suggest, apply only under abnormal post-war conditions. Under normal conditions the contracts should be placed and programmed so that the buildings are ready by the date upon which the boiler contractor is ready to start erection. On the other hand, bearing in mind the urgent requests for weather cover which the boiler contractors are liable to make when boiler erection and butt-welding of tangent wall furnace-tubes is under way, the erection time for an outdoor boiler installation may perhaps be a little longer than for an indoor boiler if there happen to be any prolonged spells of bad weather. I cannot altogether accept the author's statement that the orthodox boiler-house necessitates the use of an erection crane on the roof of the building, thereby retarding the construction of roof cover.

I am surprised at the comparatively close spacing of the main columns in the turbine house. I would have thought a spacing of 35ft centres, i.e. two spans per bay instead of three, with the mid-point of the span opposite the centre-line of the set, would have been more economical. The inclusion of a second loading bay is interesting. I admit being in favour of such an arrangement in a 4-set station, having in mind the considerable benefits this confers during the construction of the latter sets, particularly if the floors of the well openings between the sets are fairly well occupied with commissioned plant. I understand, however, that the B.E.A. tends to view with disfavour the inclusion of a second loading bay on the score of economy. Has the author any views on this point?

Mr. T. Smeaton (*at Manchester*): I am told that the Frodsham marshes are very windswept, and it seems from the orientation of the station that the boilers will be on the lee side of the turbine house, so that, while they may escape the full blast of the prevailing wind, the eddies formed by the turbine house might cause some inconvenience.

The outdoor features of Ince were based on some of the corresponding stations in the United States, notably the O. S. Hutchings plant, and the fact must be faced that there is quite a large volume of opinion in favour of this type of enclosure, despite some extremes of temperature.

In other parts of the world the reaction has been somewhat similar to that in Britain. In Germany, for example, where steel is expensive and the cost of steel-frame building is begrudged, there has been some experimenting with fairly large boiler plants having a degree of enclosure even less than that attained at Ince, in that the "umbrella" has been omitted and the boiler stands completely in the open with all the access galleries cantilevered from the boiler structure, operation being carried out from what might be termed the front of the boiler located inside the turbine house. This design has received a certain impetus, because the main building housing the turbine is of reinforced concrete and is therefore preferably independent. The layout thus achieves one of the objects sought at Ince, i.e. the elimination of the building structure by using the boiler steelwork for all structural purposes.

In many of the German stations, particularly those located at the pit-heads, a compromise has been sought by grouping together the housing for ancillary plant such as switchgear, water treatment, administration offices and welfare, etc., around the boiler, so that the enclosure is formed by these buildings. This arrangement has limited application, in that it cannot readily be used where there is more than one boiler or when the unit height is such that it towers above the buildings mentioned.

Mr. A. I. Jones (*at Manchester*): It is stated that the semi-outdoor design has eased the boiler-house ventilation problem; nevertheless the forced-draught fan intakes are shown in Fig. 2 as pulling the combustion air from a relatively restricted volume, and it appears that this might produce local draughts, and even under certain conditions a down draught on the firing aisle. I should be pleased to have further information on this point.

Another point which has a considerable influence on the height of the turbine-house annexe is the method of de-aeration adopted in the feed-heating system. The annexe indicated in Fig. 5 is the same height as the turbine-house roof and the tank level appears to be low if bled-steam de-aeration is adopted. I shall be glad if the author would elucidate this point.

It has been stated that 38% of new plant to be installed in the United States in 1953–56 will have outdoor or semi-outdoor boilers, although only 21% will have similar turbine-plant arrangements. It should be noted, however, that the savings in capital cost of housing are offset to some extent by delays in maintenance, additional heat losses and in some cases by the costs of special weather protection on individual plant items. In one case the additional heat loss from the boiler is calculated as 0·7%, which is estimated to be equivalent to 94% of the cost of the boiler enclosure. Furthermore, it is also suggested that, if emergency repairs are required in mid-winter and the outage time is prolonged by 32 hours in the year due to this cause, the incremental cost of a complete boiler-house building is more than covered.

I should like the author's opinion on this point, in view of the more accurate figures of the saving in capital costs which will now be available for the Ince station.

Mr. J. L. Ashworth (*at Manchester*): Has any special attention been given to expansion problems which might arise from the uneven temperature gradients in the boiler supporting structure? For example, the rear columns may be at or below 32°F in winter and the front enclosed columns at considerably higher temperatures.

Improved accessibility, especially at the back of the superheater and economizers, will facilitate repairs and maintenance in the semi-outdoor design at Ince. Have lifting devices been provided at the back of the boilers to make full use of this increased accessibility?

Mr. C. Ayers (*at Manchester*): Although the auxiliary switchgear appears to be in a reasonable position having regard to the whole station, it appears to be at the centre of gravity of a number of widely separated loads. There appears to be a large block of load outside the boiler house remote from the switchgear, namely

the forced-draught and induced-draught fans, precipitators, etc. A case could be made for the re-orientation of the switchgear in two groups, at the front and the rear of the station. Has the author justified the location of the switchgear in the position adopted, or have other factors had an influence upon the choice of position?

From the station plan and elevation (Figs. 2 and 3), plant access to the switchrooms appears to be possible only from the ends of the building; and that by the relative levels of the various switchroom floors, plant access to the station switchgear is possible only through the unit switchroom floors. If this is the case, a large amount of manhandling of equipment will be necessary. Could the author indicate how this has been overcome?

Reference is made in the paper to the long feeder cables; will the author indicate where the auxiliary transformers are placed, since they do not appear in any of the illustrations?

From Fig. 4 it appears that, with the steam and feed pipes as shown, some clashing between pipes and cables will occur. Will the author give his assurance that this is not so, and indicate how the problem was avoided?

Will the author indicate the use of the towers, apparently at both ends of the building between column lines C and E (Fig. 2)?

Why is so much *in situ* concrete used above foundation level, on roofs and intermediate floors; lighter construction could be employed, particularly for the roofs, which could be arranged to give adequate lighting facilities. This should be borne in mind, since the lighting problem in a power station differs from that in other buildings in that vertical surfaces have to be illuminated as well as horizontal surfaces.

Mr. C. E. Pugh (*at Manchester*): Considerable difficulty is experienced with the dust plant when starting up new power stations. This normally results in spreading dust over the buildings and equipment adjacent to the dust plant. Has the author therefore considered the possible effect of this on the outdoor equipment?

Have any cable subways been arranged from the central switchgear annexe?

What type of sheeting has been used on the station?

Mr. J. Tozer (*at Manchester*): During recent years a great deal has been said and done about welfare; in fact, welfare has now reached such proportions that consideration must be given to it at an early stage in the planning of a station. To illustrate this, one might mention the demand at a recently completed orthodox power station for electrical heating of the order of 5kW at each coal-transfer point on an enclosed coal-handling plant. This request from the operatives had to be met at considerable expense. Again, welfare now demands 3–4kW electric ovens and hotplates in operatives' mess rooms, despite the fact that a canteen kitchen is installed with a loading of about 120kW. Bearing this in mind, one wonders how welfare and semi-outdoor boiler will blend.

Mr. A. Willcock (*at Manchester*): Boiler gauge-glasses at times give trouble in the orthodox boiler-house, owing to draughts, and I should like to know whether any precautions have been taken to shield the glasses from varying atmospheric temperatures. I should also like to know whether there are any special features about the lighting used, since most of it will be outside, and whether use has been made of the reflection of light surfaces, such as aluminium paint or white tiles, round the steel stanchions.

What provision has been made for fire protection for the turbines, since it is possible that the outdoor station will run a bigger risk of involving other parts of the station than the conventional type, where provision is made for sectionalizing the units.

In a conventional station tiling has been used to reduce the cost of maintaining walls. Has provision been made in the structure with this in view?

It seems that unit construction would lend itself to the special conditions under which an outdoor station would function. The units or parts of units could be taken out and maintained in an enclosed workshop under dry conditions. One thing that puzzles me is the provision of protection for the coal-handling plant and of a locomotive shed when the object is to reduce the protection to the main plant.

Mr. H. Cahm (*at Manchester*): It is a surprising fact that we have had to wait almost until 1954 to see in this country the first developments of the semi-outdoor form of construction of the mechanical plant of power stations, whereas important electrical plant such as 132kV Grid substations, and in some cases power-source switchgear at some intermediate voltage has been installed in the open for many years. For the electrical engineer the problems of weather protection are not new.

Around the exposed parts of the boiler will be found small, but not unimportant items, such as the motors for the air heater and oil pump, and soot-blowing equipment at several levels. What provision has been made for their weather protection?

The main feature of the boiler-house construction shows that the customary steelwork uprights for supporting the roof and the cladding, particularly the rear wall, are absent; consequently the usual supports for vertical cable runs are not available. Does this justify the familiar complaint that the designers, having planned the main features without regard for the fact that important cable runs have to be accommodated, treat this matter as an afterthought?

Mr. L. C. L. Dale (*at Birmingham*): What sort of difficulty was experienced in persuading the Royal Fine Arts Commission that the semi-outdoor concept would be in keeping with the general location of the station? Those of us who are concerned with the design of power stations have often been accused of building "cathedrals," but until recently I felt that the Fine Arts Commission have more than aided this approach. I should be interested to know their first reactions to Ince.

An interesting point is the sideways segregation of the boilers, particularly the enclosures at the top level. Probably the answer to interconnection so far as access for personnel is concerned lies in the comparatively narrow bay which accommodates the main staircase.

What factors determined the type of cladding used?

Mr. G. D. Clegg (*at Birmingham*): Can the circulating water be taken from the River Dee at all times, or is a limit set by tides, particularly having regard to the possibility of the need for excessive pond purging?

Mr. J. E. Farrington (*at Birmingham*): At one time the maintenance of power-station boiler-house auxiliaries was a question of fitters being engaged in hot and dirty places, and we paid them an extra rate, known as "internal," for this sort of work. I can imagine a fitter on a rush job on the bearing of a forced- or induced-draught fan at Ince being paid "external" rather than "internal" rates for this sort of work in very bad weather. Has this been allowed for and in what way?

Mr. H. M. Fricke (*at Birmingham*): Could the station transformers have been placed nearer their control panels?

Mr. H. C. Fox (*at Birmingham*): Among the many points that should have been considered was civil defence, but it would seem to have been decided that civil defence was not worth bothering about, for a more vulnerable building I have never seen.

Mr. A. J. Mare (*at Birmingham*): Protection from frost was considered in the design of the station. What is the lowest temperature anticipated, for the station is only a few feet above sea level and is situated in a particularly mild part of the country?

Are the temperatures there during the winter higher than in this district, and does this have a bearing on the siting of future semi-outdoor power stations?

Mr. L. A. E. Fosbrooke (*at Birmingham*): From the operator's aspect I do not think that Ince will be more difficult to operate than a station of orthodox design. The arrangements for ready access to the plant under cover are satisfactory for both the operation and maintenance personnel, and the access to the outdoor sections of the plant is also satisfactory for carrying out repairs.

Renewing primary superheater tubes would involve some difficulty, as apparently the only way to remove the elements is to lift them vertically into the boiler drum housing. Since there is insufficient headroom it would be necessary to cut the tubes into suitable lengths and then, presumably, to remove one of the wall panels and lower the sections to the ground outside. In replacing the elements it would appear that the reverse procedure would have to be employed, calling for the need to butt-weld the various lengths together *in situ* in the superheater chamber. No such difficulty is envisaged with the secondary superheater tubes, for it would be possible to lower these through the combustion chamber and to withdraw them through a suitable opening in the ash hopper.

Mr. R. R. Maddock (*at Birmingham*): Table 1 shows that the difference in capital cost for civil-engineering work as compared with an orthodox station is £0·7 per kilowatt. It is evident that there is a lot of additional work necessary to guard against frost, etc., and the cost of this would reduce this difference; I cannot see how the author arrives at the saving of £1 per kilowatt.

I can foresee difficulties in maintenance which I think will mean increased cost, and I wonder whether this has been taken into account. There is undoubtedly some loss of efficiency caused by taking the f.d. fan suction from the lower part of the boiler instead of the top, and I have no doubt figures could be obtained for this.

If the stanchion spacing is such an important feature, I see no reason why any unit boiler, which is now generally slung from the main steelwork, should not have its stanchions at the spacings where the heavy load is concentrated. The stanchions could be carried up to roof height, and with light interconnected members would give much the same result as at Ince.

In the comparison of the orthodox station with Ince, do the volumes of the orthodox station envisage enclosed precipitators, and is it a brickwork or a sheeted construction?

Mr. E. H. Cook (*at Birmingham*): I like the layout of the station from the operator's aspect, but I feel that the stoker on the boiler may find himself a trifle lonely. How will supervision be carried out—by telephone or by a periodic round of foremen or engineers?

How does the author propose to handle the boiler mountings (which are too heavy to be carried) and the boiler safety valves? Must they be wheeled along the corridor at the back of the boiler to get them to the lifts, or is there an alternative method?

Mr. J. P. Cranmer (*at Birmingham*): The author says that the arrangement of each boiler on the unit principle proves very satisfactory for the accommodation of the 3·3 kV station auxiliary switchgear. While this is true for the unit boards, there is also the problem of finding a convenient space for the 3·3 kV station board, and I should like to know where this is accommodated.

Mr. H. N. Adderley (*at Birmingham*): The author says that the feed-heating plant was put by the side of the alternator to enable the crane to reach it and to utilize the space which would otherwise have been wasted. Is some other plant to be located in the space by the side of the turbines?

Mr. T. G. D. Wintle (*at Birmingham*): Has the author considered sheeting the whole of the boiler section? It has been my experience in all design problems that the simple solution is best, and from both the drawings and the artist's sketch of the station the boiler section appears complicated. The drum chamber could be kept cool by a barrier floor just as in the design, but instead of making separate covers for the various pipes that have to be protected from the weather, would it not be simpler and more economical to sheet the whole area?

Mr. H. S. Davidson (*at Birmingham*): The big problem with outdoor equipment in most parts of this country is corrosion. To what extent have the outdoor parts of the plant been specially designed to resist corrosion, what methods have been adopted, and has there been any appreciable increase in cost as a result of these precautions?

Mr. O. H. Hosking (*at Birmingham*): It has been pointed out that for this station the make-up water has to be pumped eight miles from the River Dee; why not take the station to the water or indeed right on to the water?

I do not suggest we should install 240 MW in one ship, but it would be most valuable if we could provide a number of, say, 30 or 60 MW floating standby units at strategic points, in the case of a major disaster from whatever cause.

The possibilities are evident to-day from the fact that tankers are now being built with turbo-electric propulsion, and it may be that groups of these, if provided with standard a.c. machinery, could be located at appropriate places in the very numerous estuaries around Britain, to feed power into the Grid at strategic intake points in the event of an emergency. Suffice it to say that a comparatively small fleet of, say, eight 30 MW floating units suitably located would equal the output of the Ince plant. In any case, naval atomic-powered units may be contemplated in the not distant future.

Mr. A. C. Thirtle (*at Bristol*): I do not attach much importance to the comparisons shown in Table 1, because of the difficulties of defining an orthodox station. In the station now under construction at Portishead, which will have six 60 MW sets operating at 900 lb/in^2, the enclosed volumes in cubic feet per kilowatt are: turbine room, 13·7; boiler house, 23·4; the adoption of two boilers per set accounts for the larger boiler house. Even though the total volume is greater than the figure shown for the orthodox station, the estimated civil cost for the structural framework and the superstructure is £5·65 per kilowatt against a figure of £6·08 quoted for the orthodox station.

If the objective is purely savings in cost of constructing buildings, there is probably greater scope for success in adopting economic designs of cladding both for boiler house and turbine room. The experience which will now be possible in the operation of the Ince station will encourage new ways of thinking in the design of boiler houses, which will assist in further development along these lines.

Mr. J. D. Bristow (*at Bristol*): What form of lagging was used in the exposed ducting and boiler house cladding to prevent condensation?

Mr. K. H. Shipton (*at Bristol*): The weathering of floor sections and foundations becomes a very real problem in the design of semi-outdoor power stations, and I should be interested to know what precautions have been taken to avoid rusting of steel parts, particularly around foundations where the full drainage of water and access for painting is restricted.

Mr. J. Irlam (*at Bristol*): With regard to the question of ventilation and the conditions for maintenance work, it is suggested on an orthodox layout that equally good conditions would be achieved by having the f.d. fan ducts extracting from the underside of the boiler-house roof, plus movable laylights directly over the boiler itself.

The partial cladding indicated leads to the use of more sheeting

than the minimum possible, and I wonder why this structure is considered unsuitable as it stands for conversion into an orthodox station by the enclosure of the unclad portions. While appreciating the interesting experimental angle of the semi-clad boiler house, if time, money and material were the primary motive, would it not have been better to have considered sheeting the whole structure? This (on the boiler-house side) would probably have led to some additional savings in the concrete platforms indicated in the boiler house, which would normally be constructed of light openwork steel, together with other incidental items associated with the special layout.

Mr. G. W. Clarkson (*at Bristol*): I am interested in small pulverized-fuel pressure-raising installations to avoid the use of the large mills during pressure-raising periods, with consequent flashing of boilers and wear and tear on the electrical equipment, etc. The use of a certain type of oil-firing equipment has already proved successful in pressure raising, in particular with regard to temperature control over the whole width of the superheater. Can the author provide any information after a short period of operation on the use of the "pup" mill at Ince as an alternative method?

Mr. J. R. Rylands (*at Leeds*): There is plenty of outdoor plant abroad, in the Colonies and Dominions, and especially in Canada and the United States. Indeed, were it not for our climate, it might be a matter rather of justifying enclosure than of examining the possibilities of opening out. One station in the United States has the boilers in the open, the only enclosure being for the operating staff, who occupy a large glass-sided air-conditioned control room about 50 ft long. The control panels for the boilers are of the miniature type, no dial being greater than 4 in, and no control knob greater than $1\frac{1}{2}$ in, in diameter. I saw it at the height of a grilling summer, but all was cool and pleasant in the control room. I was told that in winter, when it was freezing outside, the control room was suitably heated.

On the author's showing there is not a great deal of capital saving from this semi-outdoor construction. I should imagine the chief advantage—if it can be used and not wasted—is speed of construction, but it is obvious that this can be gained only by precise co-ordination throughout the constructional programme.

The author's calculations for the heat reclaimed by the f.d. fan seem to need modification. A figure of 13 lb of air per pound of coal would be nearer the mark than 9 lb. In other words, orthodox enclosure retains rather more heat in the combustion air than the author indicates. It is true that a lower inlet air temperature will give a lower final gas temperature, but there will be an increased risk of air-heater, and possibly of fan, corrosion. If at any time oil fuel is used, this may be very serious indeed.

Mr. C. M. Beckett (*at Edinburgh*): At drum level the sheeting has been brought back to form narrow re-entrants. Are windows provided in these re-entrants?

In a previous reply, concerning the possible use of light cranes if provision had not to be made for lifting a stator during erection, the author said that it was not feasible to put a stator into No. 2 position once the equipment had been installed in No. 1 position. Why was it not possible to deal with Nos. 2 and 3 positions first, and with the outer positions later?

Messrs. A. N. Duffett and **J. O. Knowles** also contributed to the discussion at Liverpool, **Mr. J. E. L. Robinson** to the discussion at Manchester, **Mr. G. S. Buckingham** to the discussion at Birmingham, and **Mr. N. V. Worthington** to the discussion at Bristol.

Mr. F. H. S. Brown (*in reply*): Mr. McCabe asked whether the architectural authorities have objected to the appearance of the semi-outdoor station, and the answer is categorically "no." In point of fact, many authorities appear to be of the opinion that a power station should be purely functional in architectural treatment and have welcomed the Ince type of design as a move in this direction.

I agree with Mr. McCabe that direct pumping to disposal ground and resoiling is an excellent method of ash disposal, but it was precluded at Ince by various factors, including the composition of the local top soil and subsoil. Possible icing troubles on the cooling towers will be prevented by the usual method of arranging to distribute hot water over the skirts of the towers during icy conditions.

In reply to Mr. Din, the floor at drum level is solid for the reasons he suggests, and precautions have been taken against air-heater corrosion by provision for air recirculation, in addition to the fact that the forced-draught fans pull from the enclosed sections of the station. The station is designed to burn East Midlands fuels. I quite agree with Mr. Fuller that all capital savings are worth while, no matter what the total capital cost of the project.

Mr. Steinbock raises the question whether more plant should have been out of doors and also whether the plant arrangement is the optimum. The first point is controversial and must be largely a matter of opinion until operating experience has been gained; as regards layout, there are, of course, almost endless possibilities, but on examination it usually appears that the normal in-line arrangement has many advantages.

Mr. Steinbock also criticizes the thermal conditions at Ince, but the paper is on Ince alone, which contains standard 60 MW machines, and it does not attempt to discuss the current advances in steam cycle which the Authority are, and have for some time been, adopting at sites better adapted for their application than is Ince.

Mr. Stowell appears to have misunderstood the reference to pipe runs. The paper does not say that vertical pipe runs are unique to Ince, but merely describes the way in which the enclosure protects such pipes from frost. Similarly I feel that, if he compares the profile of the Ince station with that of Portobello, he will find that there is appreciably more outdoor plant at the former than at the latter.

On Mr. Pilling's question about American opinion on semi-outdoor stations, I do not think that any generalization can be made. Some American engineers are enthusiastic, others are not, and the most that I can say is that according to current publications some 25% of the stations planned for installation in a typical year—1954—were semi-outdoor.

On the provision of the basement at Ince: I would not suggest that this is an advantage as such, but since foundation conditions forced excavation, advantage of the fact was taken to enclose the ash-hopper floor by the method described. The foundation costs quoted in Table 1 refer to virtually all the civil works on site.

Mr. Bateman's point about cladding areas is incomplete. The Ince design—as must be all power stations—is an integrated whole, and it is not permissible to argue on any one point without considering its effect upon others. Alterations to the system of enclosure has repercussions upon many items, e.g. roof areas, access clearances, etc., and simple arithmetic is not applicable.

I accept Mr. Mahon's point that boiler access after only limited erection of steelwork is of more importance during abnormal post-war conditions than in more ordinary times, but it has, I feel, some value even then. The point about roof cranes made in the paper is only a marginal one to demonstrate that complete weather protection to the boiler erection is not always possible; as a matter of interest, no such crane was used at Ince.

In answer to Mr. Jones's comment on ventilation: it is felt that the Plenum chamber formed by the ash basement will be large

enough to prevent local draughts from the forced-draught fan suctions, and provision has been made for direct intake to the fans from the open air if the down draught of warm air past the firing floor is found distressing in hot weather. High-level de-aeration is not employed at Ince. The figures given on American practice are interesting, but only operating experience will give the figures he requests for Ince.

The structural expansion difficulty feared by Mr. Ashworth should not arise. The boiler structure is tied to the main building by light transverse members only between column lines D and E.

In reply to Mr. Ayers, the switch-houses are individual to each main unit, and a gap of some 15 ft wide, measured longitudinally, exists between each of the four houses. This gap is the full height of the basement, it provides access to each end of both levels of switchgear, and also through-access for men, steam and feed pipes and cables, etc. The auxiliary transformers are adjacent to the generator transformers on the west side of the turbine house. The roof is not concrete, but of light cellular construction over both boiler and turbine rooms.

The reasoning behind Mr. Cahm's point on cable runs is well appreciated. These were considered at the same time as and given equal importance to pipe runs and maintenance access, etc., when the preliminary layout of the station was being developed, and as a result have been incorporated in the design neatly and without any trouble. Early consideration of cable runs is, in my opinion, quite vital to a successful and fully integrated design.

The architectural point raised by Mr. Dale is interesting, and authorities appeared on balance to welcome the Ince type of design as promising a functional approach to what is regarded as the difficult problem of power-station architecture. Equally, the civil-defence aspects of the design were approved without difficulty.

The circulating-water make-up is taken from the Dee just above Chester weir, and is therefore unaffected by tidal variations. The cladding used on the boiler structure is of a proprietary sheeting, aluminium-coloured externally. The 3·3 kV station switchgear is located in the same bay as is the unit switchgear, there being two floors of switchgear—one unit and one station. The boiler drum mountings, etc., can be hoisted to drum level either in the station lift or, if necessary, through the gaps between boilers. The feed pumping and heating plant is located alongside the whole length of the machine, with due provision for condenser-tube withdrawal, and not alongside the generator alone—which is the impression Mr. Adderley appears to have received. The boilers are controlled on the combined boiler-turbine instrument panel situated in the engine-room annexe at the operating floor level. No special steps were taken against steelwork corrosion other than some special care in painting; special measures were considered but proved much too expensive.

I understand from contact with the operators since the station was commissioned that the "pup" pulverizing mills have proved enormously useful, particularly during the commissioning period, and Mr. Clarkson might be interested to know that virtually all pressure raising and early running, while the inevitable adjustments were made to the main plant, was done using the "pup" mills.

Windows are provided in the re-entrant cladding at drum level.

Mr. Thirtle's figures for Portishead are interesting, and, of course, as both he and Mr. Maddock point out, any comparative figures given in support of a semi-outdoor design must be open to debate. The paper itself is careful to point this out, but clearly it was necessary to give the best approximations available as to the relative capital costs, etc., given by a semi-outdoor design; no such figures can, however, be authoritative, involving as they do comparisons between separate power stations. I will be more than content to let the final ascertained costs for Ince, segregated to any desired degree, stand in comparison with contemporary equivalent stations of orthodox design, and allow what conclusions may be drawn from the comparison.

DISCUSSION ON "THE CO-ORDINATION OF INSULATION OF HIGH-VOLTAGE ELECTRICAL INSTALLATIONS"*

NORTH MIDLAND CENTRE, AT LEEDS, 4TH JANUARY, 1955

Mr. A. J. Coveney: The author states that an effectively earthed system is one in which the phase-to-earth voltage does not exceed 80% of the phase-to-phase voltage. He then states that this is obtained when the ratio of the zero-sequence reactance to the positive-sequence reactance is less than 3, and when the ratio between the zero-sequence resistance and positive-sequence reactance is less than unity. I suggest that we simply accept the statement that a system is effectively earthed when the maximum voltage to earth does not exceed 80% of the phase-to-phase voltage. Moreover, I understand that the ratio statement is not rigorously correct and does not always agree with the 80% figure; therefore this causes confusion.

The author states that, on systems in which the neutral is earthed through a resistor, the fault duration is not more than a few seconds. Surely this can apply also to solidly earthed systems if we have any confidence in our protective systems. Has the author some reason for omitting this system from his statement?

It is stated in Section 2.2.1 that after the first restrike the line is left charged at twice the normal phase-to-earth voltage. Actually if the restrike takes place half a cycle after current zero—the condition mentioned by the author—the over-voltage can reach a figure of 3 times the peak value of the phase-to-neutral voltage. In practice, however, the presence of damping in the circuit reduces this figure, but I think it is more correct to assume a value of 3 rather than the value of 2 given by the author.

It must be appreciated that a restrike at half a cycle after current zero is the worst possible condition, and one most unlikely to occur with a modern high-speed circuit-breaker. With modern circuit-breakers restrikes usually occur in the first quarter-cycle after zero current, and the over-voltages are therefore proportionately less.

Some years ago on a large system (at 6·6 kV) on a cable

* Cliff, J. S.: Paper No. 1485 S, March, 1953 (see 101, Part I, p. 39).

network a series of breakdowns occurred, always at week-ends when there was no industrial load and the system was lightly loaded. A routine was organized to switch off as many feeders as possible, and this proved a remedial measure. In fact, shunt capacitance was reduced, the over-voltages were lowered and breakdowns on cable boxes disappeared

With further regard to restriking at half a cycle after current zero, whilst this may occur on oil circuit-breakers, it is impossible for it to happen on some designs of modern air-blast circuit-breaker because the electric strength of the contact gap increases so rapidly that it is able to withstand twice the phase-to-neutral voltage at half a cycle after current zero. Users of this design of circuit-breaker, therefore, will have no over-voltages arising from this phenomenon.

A point of interest hardly concerning co-ordination is a phenomenon which sometimes occurs when closing a circuit-breaker on to circuits with large capacitance. Once or twice when closing a metalclad switch I have observed a number of sparks jumping from one metal part to another and not necessarily to the earth bar. This oscillatory discharge, caused by a steep-fronted wave on a high-capacitance circuit, is only momentary and is quickly damped out. However, it can have deleterious effects on relay coils.

In Section 2.2.1 it is stated that "again the over-voltage *depends* on the type of circuit-breaker." I think that system conditions can cause over-voltages just as readily as the circuit-breaker, i.e. that circuit constants are as important as circuit-breaker characteristics.

The modern air-break circuit-breaker which automatically introduces resistance in the circuit does not produce over-voltage. The modern high-speed oil circuit-breaker does not permit restrikes after the first half-cycle following current zero on these line conditions. It is really the old type of slow-break oil circuit-breaker which is liable to this fault.

With regard to over-voltages produced by lightning, it has been common practice in the past to over-insulate overhead lines above British Standard recommendations. They are then connected directly to switch panels. Some co-ordination is required to prevent, say, 11 kV lines, with insulators having flashover voltages associated with the values usually given to switchgear suitable for 22 kV, being connected direct to switchgear.

If a convenient flashover point or lower-level discharge point could be established on the line, economy would be effected and less stress would be set up on switchgear. I know of one case where, during a lightning storm, a 33 kV line connected to a 33 kV metalclad panel resulted in a breakdown on the voltage transformer, over a distance of $5\frac{1}{2}$ in under oil, with disastrous results. Obviously a need exists for some safety gap or effective surge diverter.

Another danger, although perhaps outside the scope of the paper, is where telephone wires are run under an overhead line. A case occurred where the cable used to connect the telephone wires from the last pole to the instrument in the substation was not properly earthed and the safety gap was inefficient, with the result that an operator received rather a bad electric shock during a storm when using the telephone.

I should like to indicate the need for regular power-loss tests to be carried out on all bushings of the synthetic-resin type. Experience has shown that this is necessary, particularly on busbars. Efforts are now being made to arrange for power-factor tests by means of a Schering bridge, capable of being used whilst the bushing is in service. Would the author comment on this and consider whether some test values should not be established for the safety of the gear?

Mr. E. A. Kimber: In Section 2.2.2 the author mentions the effect of lightning strokes on overhead lines, and in Section 2.3 he states how these lines should be protected; but although the type of protection is mentioned it is not indicated where the surge diverters should be fitted in order to be of the greatest use. There appears to be a divergence of opinion among engineers on this point. Some consider that a surge diverter should be placed at the junction of the overhead line and underground cable, while others consider that a diverter placed in the middle of a long section of overhead line is just as effective. Has the author any suggestions on this point?

Has the author any information on indicators for use with diverters, because if an engineer fits diverters he is always interested in whether they have operated or not? Some simple device with either a Post Office type of counter or simply a resettable flag would be useful.

Mr. P. H. Sinclare: Overhead lines for voltages above 66 kV are normally erected on broad-base towers and protected by one or more aerial earth-wires. Difficulties in obtaining low tower-footing resistances are not as great with this type of construction as with the wood-pole lines used for lower voltages, and can be reduced by counterpoise. A very high proportion of external over-voltages are dealt with by the earth shield, and surge absorbers appear difficult to justify on systems above 66 kV except in special circumstances such as the new unearthed 132 kV overhead lines.

The tendency to rely on a good earth shield is very apparent in Germany, where many new earthed 100 kV lines are being built, some with as many as three earthed conductors. Previous practice in that country was to use individual tower earthing and to rely on arc-suppression coils and surge diverters for protection.

I believe that the main future application of surge diverters will be in the lower voltage (i.e. 5–66 kV) range, in order to reduce the number of supply interruptions caused by rod-gap operation. Can fuses and diverters, and rod gaps and diverters, respectively, be co-ordinated satisfactorily? Should diverters be installed at every transformation point, or would diverter installations at the points of greatest hazards, i.e. at line terminations only, prove satisfactory?

It seems that the auto-reclose circuit-breaker will compete with the diverter as an efficient means of maintaining continuity of supply during thunderstorms; the former method avoids the necessity of fitting numerous pieces of equipment which themselves represent additional hazards. Figures for diverter breakdowns are not easily obtainable, and I wonder whether the author has any information on the subject.

Prof. G. W. Carter: In discussing the apparatus which may be connected to high-voltage systems, the author does not mention alternators. Owing to the nature of the winding of an alternator and the impossibility of using oil for insulation, it is difficult to attain an insulation level as high as in a transformer, especially under surge conditions. In spite of this, a certain number of alternators have been wound for 33 kV and connected directly to overhead transmission systems. I should be interested to have the author's comments on this practice, and also on the general problem of insulation in relation to alternators.

In Fig. 1, curve (g) representing the protection level of a surge diverter is shown as turning downwards at its left-hand extremity. Since the diverter incorporates series gaps which must have a small time lag, the curve should surely bend upwards here in the same manner as the adjacent rod-gap curves.

The author mentions that lightning discharge currents may be as high as 160 kA, and yet it appears that the performance of surge diverters is based upon a maximum current of 20 kA for low-voltage systems and 5 kA for high-voltage systems. Does this mean that discharges of higher currents, although possible, are statistically so improbable that the acceptance of 20 kA is a

reasonable risk? A current of even 5 kA discharged into the impedance of an overhead line will generate so high a voltage as to cause insulator flashover. It is therefore not possible for so large a current to penetrate a portion of line protected by earth wires in the form of a travelling wave.

Mr. J. S. Cliff (*in reply*): For the purposes of a definition of an effectively earthed system it would be possible, as Mr. Coveney suggests, to specify only that the voltage must never exceed 80% of the phase-to-phase voltage. In practice this must usually be ascertained by calculation, and it is found to be dependent upon the ratios of the resistive and reactive components. The values quoted are frequently used as an approximate guide, giving an answer which errs on the side of safety. In doubtful cases the full method given in the Reference quoted in the paper is used.

With regard to the interaction of circuit-breaker and system in the production of internal over-voltages, Mr. Coveney quotes only the first part of the sentence in the paper, and fails to notice that I have also emphasized that it is the combination of circuit-breaker and system which must be studied. It is quite true that the various types of circuit-breaker react differently, and modern designs are undoubtedly better for dealing with capacitive currents. Taking into account the thousands of circuit-breakers of all types and ages which are in service on widely differing systems, it must be recognized that internal over-voltages are not a major problem, and only need special consideration in a few abnormal cases.

The characteristic curves shown in Fig. 1 can be taken as typical in shape for other system voltages, in addition to 132 kV, and emphasize the point made by Mr. Coveney that overhead lines in general cannot alone protect the terminal apparatus, and it is essential to provide some form of over-voltage protection for the switchgear and transformers. The most effective protection is provided by surge diverters, and in answer to Mr. Kimber, these should be located as close as possible to the equipment to be protected. When surge diverters are installed along the transmission line, it is usually because it is considered necessary to reduce line flashovers at those points. On the more important lines it is more effective to use overhead earth wires, as mentioned by Mr. Sinclare, particularly where low earth resistances can be obtained. As the system voltage increases, the earth-wire shielding, in general, becomes more effective, and for that reason surge diverters become less necessary. On the other hand, at the higher voltages the consequences of a breakdown are much more serious and surge diverters are frequently justified, particularly if by using them it becomes possible to use apparatus having a reduced insulation level and lower cost.

As Mr. Sinclare states, a combination of auto-reclose circuit-breakers and rod-gaps can give reasonable protection, particularly on rural lines where circuit reclosers can be used, but at the higher voltages the cost and reliability of the special relaying which is necessary for auto-reclose operation makes the scheme uneconomical for lightning protection alone. I have previously commented on the reliability of surge diverters.

As Prof. Carter points out, the insulation strength of alternators is inherently low, and for this reason they are seldom connected to overhead lines, except in relatively small and unimportant installations. Special designs of surge diverter are available having lower residual voltages, and these in combination with protective condensers at the machine terminals for reducing the steepness of the voltage wavefront, and hence the inter-turn stress on the windings, will give reasonable protection. In the majority of installations the alternators are protected by the transformer, with surge protection on the h.v. side of the transformer, and very little trouble is experienced.

The current of 160 kA mentioned by Prof. Carter referred to a direct stroke to a solidly-earthed conductor. Such high currents would not flow through a surge diverter. Measurements of current through surge diverters in service have shown that 20 kA is approximately the maximum, and this occurs extremely rarely, so that basing insulation on the currents given in the paper is a reasonable risk.

Mr. Coveney mentions the desirability of checking the dielectric power factor of s.r.b.p. bushings during their life in service. This can be done with special Schering-bridge installations, but as the ionization at the working voltage is very low and is dependent upon the temperature of the insulation, it is difficult to draw reliable conclusions from the results unless a marked increase in power factor is observed which persists. In such a case the bushing should be removed for examination and checking of the power-factor/voltage characteristic under laboratory conditions. Owing to the differences in behaviour of the various types of bushing, it is premature to fix test values for service measurements.

WRITTEN DISCUSSION ON "DISTORTION OF TURBO-ALTERNATOR ROTOR WINDINGS THROUGH THERMAL STRESS"*

Dr. L. E. Benson: The author is correct in believing that the copper shortening problem is not merely a question involving the hardness and softening characteristics of copper but involves the creep strength of the material. He is correct also in believing that the creep strength is not necessarily related to the hardness.

There has been a certain amount of confusion on this point and it will perhaps be helpful to refer to Figs. A and B, which show graphically some of the information derived from the creep tests made by the British Non-Ferrous Metals Research Department (see Reference 7).

On both sets of creep tests there is good agreement between the plotted points irrespective of the degree of initial cold work and the intial hardness. This is an important point and the good agreement can hardly be a coincidence.

The softening curves are included to show that appreciable softening was not taking place during these tests. There is some reason to expect, however, that if the temperature is so high that marked softening occurs the creep characteristics will be modified detrimentally. For generator windings there is good reason for not employing material which has been cold worked more than necessary to give the very soft annealed material reasonable elastic properties. This is because further cold work seriously reduces the time at any given temperature for softening to occur. For silver-bearing copper, for example, the time for appreciable softening to occur is reduced to one-tenth if the cold reduction is increased from 10% to 25%. For silver-bearing copper 10% cold work giving a 0·01% proof stress in tension of about 7–8 tons/in^2 and a 0·1% proof stress of 13–14 tons/in^2 would appear to be adequate, and there is no advantage in going to a

* REAY, D. B.: Paper No. 1813 S, June, 1955 (see 102 A, p. 349).

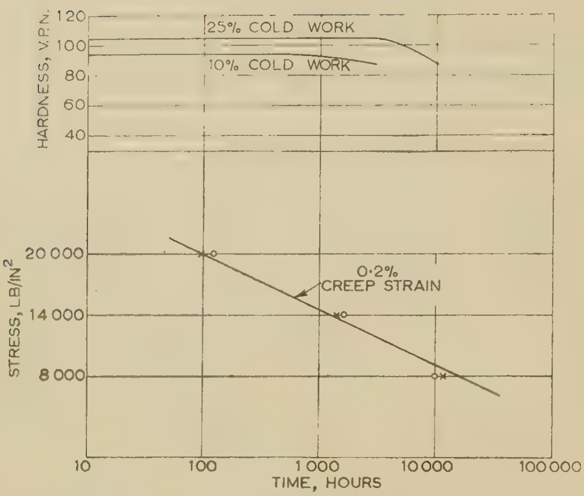

Fig. A.—Curve of stress plotted against log time for silver-free tough pitch copper for 0·2% strain on creep testing in tension at 130° C.

× × × 10%, ○ ○ ○ 25% } cold worked.

Initial proof stress (0·01% *plastic strain*).

Cold worked { 10% : 16 100 lb/in^2, 25% : 18 200 lb/in^2 } approximately.

Initial proof stress (0·1% *plastic strain*).

Cold worked { 10% : 30 000 lb/in^2, 25% : 38 000 lb/in^2 } approximately.

Softening curves to the same time scale are also given.

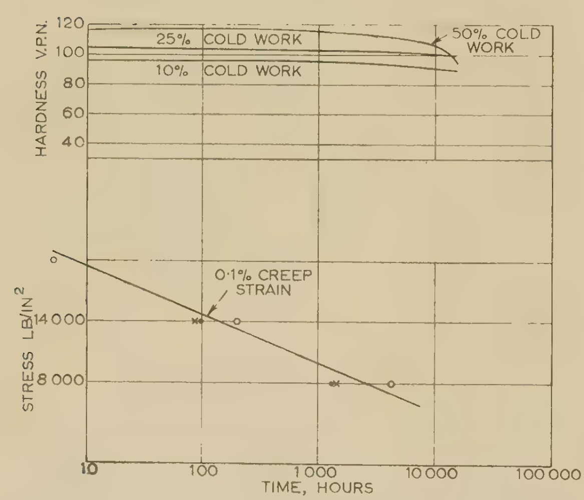

Fig. B.—Data similar to that of Fig. A, but for silver-bearing copper for 0·1% strain at 225° C, together with softening curves.

× × × 10%, ○ ○ ○ 25%, ● ● ● 50% } cold worked.

Initial proof stress (0·01% *plastic strain*).

Cold worked { 10% : 16 400 lb/in^2, 25% : 18 700 lb/in^2, 50% : 27 000 lb/in^2 } approximately.

Initial proof stress (0·1% *plastic strain*).

Cold worked { 10% : 30 000 lb/in^2, 25% : 38 000 lb/in^2, 50% : 46 000 lb/in^2 } approximately.

higher figure. Such material will not soften appreciably in the full life of a generator at temperatures well above present winding temperatures.

It seems unfair to criticize such a valiant effort, but I expect the author will be the first to admit that the creep strains for 100 000 hours given in Fig. 4 have been derived from such extended extrapolations that they need to be used with great reserve. The creep-test data from which Fig. 4 was derived were not, in fact, intended to provide a basis for extrapolation to such long times. However, within reasonable limits of stress and temperature it did indicate a temperature advantage of nearly 100° C for the silver-bearing material in respect to both softening and creep characteristics; and as I indicated in the discussion* of the paper by Benson, McKeown and Mendes, there is good reason for believing that this advantage will be maintained for periods extending to the full life of a turbo-generator.

Mr. W. J. Gilson (*United States*): Although there has been some difficulty in the United States with coil distortion in some of the older fields, the problem has apparently not been so acute as in South Africa.

In America it has been found that the use of cold-worked silver-bearing copper, together with conservative schemes of ventilation and resulting lower hot-spot temperatures, has greatly alleviated the problems connected with field-coil distortion. There remains, however, the abrasive wear and tear on the insulation due to the slippage of the field coils under the wedge while subjected to high centrifugal forces. This wear and tear is definitely a function of the number of starts and stops of the generator, as is also distortion caused by overstress (above yield strength).

It has been found that field preheating† is beneficial in reducing field-coil distortion as well as wear and tear on the insulation. Transformer heating where the generator is directly connected should not normally be a problem if the generator voltage per cycle is kept within reasonable limits.

The author has apparently misunderstood the reason for using the special outer frame for some extremely large generators in order to meet shipment limitations. The design rating of a generator may generally be increased by (*a*) increasing the active length, (*b*) increasing the active diameter, or (*c*) a combination of (*a*) and (*b*). The active length of a high-speed generator field is limited by various mechanical considerations. The permissible diameter of a field is limited by rotational stresses. The use of aluminium for field windings with about 60% of the conductivity of copper and one third of its density makes it possible to increase generator ratings by increasing field diameters within established stress limitations. As a matter of interest, we believe the aluminium alloy to which the author refers is one containing iron, silicon and magnesium.

The values for the coefficient of friction given in the paper look somewhat high. Fairly extensive laboratory tests were recently made here in order to determine the friction coefficient for the insulating materials used in our field windings. It was found that the coefficient of friction increases somewhat with decrease in normal pressure, and was about 0·12 with the pressures usually existing between the top turns and the slot wedges.

We are in complete agreement with the author's conclusion that the compressive forces induced in the field-coil turns are induced primarily by the frictional forces between the coil as a whole and the bottom of the coil slot wedge. The differences in temperature between the turns, and the increase in the coefficient of friction with decrease in normal force between succeeding lower turns, may readily account for the fact that the lower turns tend to show the greater deformation.

In a generator field winding the compressive forces are principally due to differences in temperature and temperature expansion coefficients between the steel body and the winding proper. However, there is also a shortening effect on the steel

* *Journal of the Institute of Metals*, 1952, 80, p. 682.

† GILSON, W. J., and TAYLOR, H. D.: "Field Preheating for Large Turbine Generators," *Transactions of the American I.E.E.*, 1954, 73, Part III B, p. 1375.

body due to rotational forces. These effects combine to produce a compressive strain, which causes a compressive stress to be set up in the coils.

Relaxation is normally considered to be a change in stress with time for a constant strain—whilst creep is a change in strain with time for a constant stress. With hard copper, therefore, the field-coil distortion problem is one of relaxation rather than of creep, for each period of operation.

Each time the generator is started up the differential strain causes a compressive stress in the field coils. This stress will tend to decrease as relaxation of the field-coil material becomes effective. Initially the relaxation rate may be relatively rapid, but it tends to decrease if there is appreciable reduction in stress. It therefore follows that the coils may well be subjected to much more relaxation with a large number of starts and stops than if held at speed and steady load for a long period of time.

The author's calculations are interesting and similar to those which we have made. It may be pointed out, however, that there is a temperature differential along the length of the coils as well as along their depth. The warmest part of the field is normally at the centre of the field body. Since this is the section which is under the greatest frictional restraint, the relaxation will also be greater.

Mr. W. D. Horsley: The theory of frictional restraint was originated by the author following his experience with soft-copper windings. It is therefore appropriate that he should now present a paper extending his theory to the use of hard drawn silver-bearing copper and taking into account the effect of the creep characteristics of this material and of the latest methods of ventilating rotors.

The author rightly considers that any coil shrinkage which may develop in rotors having windings of c.w.s.b. copper will be due to the effect of creep and works out his examples on this basis. In Section 9.2 he reaches the conclusion that while frequent starting and stopping is an important factor where super-elastic strain occurs, the total time a machine has been on load must be taken into account in assessing creep rates. In his investigations on discarded deformed windings of soft copper he deduces from hardness measurements that the deformation was due primarily to creep strain and not to strain beyond the elastic limit. It is difficult to correlate this with the observed fact that in rotors which have run for ten and more years and shown little coil distortion, excessive coil shrinkage has developed in one to two years after having operated on the "two shift" system.

In Section 5, eqn. (6) is used to determine the coefficient of friction, for which purpose it is assumed that the compressive stress attained at the point where sliding stops is equal to the yield point of the material at that position. The curves in Fig. 1 relate to soft-copper windings and the sliding distance is measured from these curves. It is thought that considerable errors can arise in the determination of the coefficient of friction depending upon the value of stress which is assumed to be in the copper. Experience has indicated that a large amount of deformation can occur at stresses well below the yield point of the copper. The stress necessary to produce the deformation shown in Fig. 1 may therefore be appreciably less than is assumed by the author, and on this basis the coefficient of friction may be only one-half of the figure determined by the author. As previously recorded, the coefficient of friction determined experimentally on sample strips varied between $0 \cdot 1$ and $0 \cdot 3$.

In Section 6 the author gives good reasons for using his formal analysis based on temperature of the copper relative to the rotor body; nevertheless, in considering the restraint of expansion which is offered by the rotor forging, it seems difficult in practice to decide upon the true reference point, i.e. the top turn or the rotor forging is determined by the coil retaining wedges. It is accepted that the restraint between the windings and the side of the slot is negligible. In many designs the slot wedges adjoining the pole centre are made of steel, while those at the mid-position between poles are of brass or bronze, having a higher coefficient of expansion than steel. The analysis of the deformation of rotor coils has failed to reveal any difference between the distortion in slots containing steel or brass wedges. There is reason for believing that the wedges themselves expand and contract with temperature changes, and for this reason clearance is left to permit relative expansion of the wedges, particularly where the coefficient of expansion is greater than that of steel. Furthermore, the wedges are inserted in short lengths. It may not therefore be strictly correct to take the wedges as a fixed reference point.

In this Section the author also considers what would happen in the event of the system of force in the stack becoming self-balancing, and while his argument appears to be sound, it is possible that, since the creep in tension may be much less than the creep in compression, a stack of strips could be self-balancing in regard to stress distribution, but that deformation of the strips which were in compression, i.e. those towards the bottom of the slot, could occur.

At the end of Section 7 attention is drawn to Table 1, where the stresses in each of the turns have been worked out, and to the assumption that, if the reference point was the top turn, it would be necessary to reduce the values of stress in each of the turns by $4\,300\,\mathrm{lb/in^2}$ so that the stress in the tenth turn would be reduced from 19 000 to $14\,700\,\mathrm{lb/in^2}$. The difference is small and it also appears on this assumption that possibly the top two turns would be unaffected and that progressive deformation would build up on the third, fourth and succeeding turns. This would be in accordance with observed deformation.

Turning now to Section 9.1, I agree with the author that with a stress of $19\,000\,\mathrm{lb/in^2}$ and a Young's modulus of $16 \times 10^6\,\mathrm{lb/in^2}$ the strain is $0 \cdot 12\%$. It appears that to allow for the actual strain being in the reverse sense to the cold-work strain the author has multiplied the calculated figures of strain by three. It is suggested that the amount of creep corresponding to $0 \cdot 12\%$ strain should be determined and that the amount of resulting creep should be multiplied by three.

At the beginning of Section 9.2 the author demonstrates that the amount of relaxation which occurs owing to a steady creep is small, and that on 2-shift working it is therefore necessary to examine its influence only in continuous working periods, say 130 hours. Some relaxation must occur, but if the reduction in stress due to relaxation could be neglected because the steady creep rate is so small, it seems that the steady creep rate could also be neglected. I therefore consider that some allowance should be made for the effect of relaxation.

With reference to Section 11, experiments have been made on a rotor in which a number of small-bore plug test holes, designed to hold substances having various melting points, were drilled in the rotor wedges to obtain some information relating to the temperature distribution under test conditions, but great difficulty was experienced in the interpretation of the results obtained. Temperature indicators based on the colour-change principle for temperature measurement have also been tried, but these paints have pronounced temperature/time characteristics, and a great deal of experimental work was necessary before any use could be made of them. Again, the results were not satisfactory. Where temperature differences are very large, temperature indicators are useful, but for small temperature differences, as would be expected on the surface of an alternator rotor, indicators are not sufficiently accurate to give reliable information.

In calculations of the type dealt with in the paper it is difficult

to assess accuracy of the predictions made. I consider that the value of the paper would have been enhanced if the calculations had been applied to a rotor having non-silver-bearing annealed-copper windings, on which the known amount of deformation could be correlated with the theoretical analysis and the calculations then repeated, taking into account the superior properties of silver-bearing copper. As is known up to the present, rotors having silver-bearing copper-windings have not shown any indication of rotor-coil contraction.

Mr. W. N. Kilner: The author's summary of the known information, and the results of his own practical and theoretical investigations, form a valuable contribution towards the understanding of the copper shortening problem.

Apart from the rotors referred to in Juhlin's paper,[6] copper shortening has been detected on only two rotors manufactured by the organization with which I am associated. They had windings of annealed tough pitch copper. We have a number of rotors, similar in diameter and body length to the Electricity Supply Commission of South Africa rotors which failed, which have been in successful service for many years. They have soft-copper windings, and similar specific electrical loadings, but since they have never been opened up for inspection we cannot say whether any shortening of the winding has occurred. Their successful operation may be due to the machine loads having never exceeded their assigned ratings, but it is known that they have operated with average rotor-winding temperatures up to at least 113° C. Larger 37 in diameter rotors running at 3 000 r.p.m. with soft-copper windings, installed during the years 1936 and 1937, have also operated with rotor-winding temperatures up to 110° C without failure.

Large rotors with c.w.s.b. copper windings have been in operation since 1948 without showing any signs of trouble due to copper shortening. The rotor with the longest service has operated at temperatures up to 110° C, and has been stopped and re-started over 200 times. Other rotors, including some of 37 in diameter, have operated for a shorter length of time at temperatures up to 109° C.

The winding temperatures may have exceeded the figures quoted above, since it is difficult to obtain complete records of operation over long periods of time.

I agree that one of the important factors in preventing copper shortening is to have a minimum temperature gradient between turns, and the best way of achieving this is by methods of ventilation which give uniform cooling of the steel rotor teeth, or in later designs by bringing the cooling medium into direct contact with the copper. We also favour in certain designs, the use of graded windings mentioned by the author. Such windings have been fitted in rotors of generators having ratings up to 75 MVA.

Packing in the corners of the coils is valuable from the point of view of tending to prevent short-circuits between coils if copper shortening occurs.

The author has had experience with the operation of large rotors wound with tough pitch hard-drawn copper, and it would be interesting to know whether these windings have deformed, and if not, how long they have been in service. Were the severely deformed windings mentioned in Section 2.2.4 made originally from hard drawn copper?

The safe amount of copper shortening quoted in Section 10 does not appear to me to be excessive, since it is unlikely that any rotor will be required to operate at the full permitted average temperature rise for the whole of its life. It may also be more economical to rewind a rotor after 10 or 15 years of service, than make the whole generator larger, more expensive, and probably less efficient, in order to obtain a lower temperature rise.

Operating engineers can contribute towards the prevention of copper shortening by not overloading generators above their rated capacity, even for short periods. They should appreciat that when a manufacturer provides a good margin on th exciter—usually in order to minimize exciter maintenance—i does not follow that the generator rotor winding is capable o carrying the full rated exciter output.

Messrs. C. M. Laffoon and **R. A. Baudry** (*United States*): The distortion of the conductors of turbo-generator roto windings is a subject of much interest to both designers an users of turbo-generators. The turbo-generator rotor windin system including the conductors, insulation, and spacer block is considered to be an expendable part of the machine. Th generator design engineer is interested in providing a windin system that will give trouble-free service for a reasonably lon period of time with the generator operated within its contra rating under normal operating conditions and given reasonab maintenance. A quantitative calculation of the dimensiona changes of a rotor winding when operating under known o assumed loading conditions is tedious to make and is of litt quantitative value except for comparison purposes, owing t the wide variations in some of the important variables that ar involved.

The winding distortion experienced on certain American roto using annealed copper for the conductors does not approach th magnitude reported by the author for the generators under hi observation. Some American generators designed and bui prior to 1920 experienced winding distortion trouble and had t be rewound. These machines were designed for and operated a an average temperature rise of 100° C, and the maximum coppe temperatures were well above 150° C. The large number o 1 800 r.p.m. units designed and built during the 10-year perio from 1920 to 1930 for ratings ranging from 25 to 100 MV had appreciably lower temperatures, and only a few instances o conductor distortion have occurred. Many of these units ar still in service with their original annealed copper windings.

Some of the factors affecting conductor distortion are qui definite, such as speed, rotor diameter and length, conduct number and dimension, and average winding temperature. Th properties of the conductor material such as work hardening strength and ductility, creep rate, and relaxation characteristic can be determined for different temperatures, but in the actua machine they may change with temperature and time. Th temperature gradient for the rotor body in an axial direction, an the gradients for the rotor winding in both radial and axia directions, can be calculated with only a fair degree of accurac Very little reliable information is available on the magnitude o friction coefficients between adjacent conductors, and betwee the slot wedge and the adjacent winding conductor with respe to insulation materials between these parts and for differe temperature conditions. It is thus obvious that the designe must find an adequate solution to this problem by making comprehensive analysis of the effect of the different variabl involved and then carefully relating experience results to th materials and construction used, and the operating conditio such as loading, cycling, and starting and stopping. It was fro this type of approach and analysis that an explanation of th cause of the trouble was developed and the following tw corrective measures introduced:

(*a*) The material of the rotor conductors was changed fro annealed or soft copper to work-hardened copper so that it wou not be stressed above its elastic limit over the "locked-in" portio The use of work-hardened copper for turbo-generator rotor win ings was begun in 1930 by the organization with which we a associated, and was introduced for all large rotors built up to 194 There has been no case of measurable rotor-winding distorti observed on any of these turbo-generator rotors with wor hardened copper conductors built during the above period and operation up to the present time. This record applies to a ran of ratings from 12·5 MVA at 3 600 r.p.m. to 183 MVA at 1 800 r.p.m

The latter unit, which was of 60 in diameter and 270 in length was started and stopped daily during the first several months of operation.

(*b*) During the period from 1939 to 1943 an investigation was made to determine the creep-rate characteristics of annealed and work-hardened copper, and to develop a copper alloy which would have a much lower creep rate. Of the several suitable alloys developed, a silver-bearing copper alloy with 0·01–0·016% silver had the lowest creep rate and the highest conductivity coefficient.

The use of high-conductivity work-hardened silver-bearing copper alloy for turbo-generator rotor windings was begun in about 1944 and has been used on all large units since that time. Of the few units examined, none has shown any observable evidence of conductor distortion, and it is expected that this performance record will continue for an appreciable length of time.

The application of inner cooling to turbo-generators has materially changed the situation with respect to conductor distortion. For large units the improved cooling results in approximately 15% reduction in rotor diameter and length, and for a given rating its overall distortion producing factors correspond to those of a conventionally-cooled generator of half the rating. The ventilating circuit for each rotor conductor is identical with respect to inlet and outlet coefficients, length of path and back pressures, ventilating surfaces, and blower pressure, so that the temperature gradient from the bottom to the top of the coil is zero for any axially located section of the coil. This means that there is no thermally produced force tending to move the turns with respect to each other. The ventilation system can be designed so that the rotor body operates at a higher temperature than for conventionally cooled units, which results in a lower temperature differential between the winding copper and the surrounding iron. This in turn reduces the magnitude of the overall force tending to move the rotor winding with respect to the supporting wedges and intermediate insulation fillers. Thus the application of inner cooling has made possible the building of 3 600 r.p.m. turbo-generators for ratings up to 300 MW with rotor distortion characteristics comparable to those existing on machines of conventional design for ratings of 100–150 MW.

New insulating materials, when properly processed, fabricated, and applied between the top turn of the rotor winding and the supporting wedges, reduce the friction coefficients between these parts to a small fraction of the values used by the author and normally used by others in study calculations. With a much lower friction coefficient, all of the rotor winding copper would be free to move throughout the entire rotor length for generator ratings of 300 MW and higher. Although this development practically eliminates rotor-winding distortion due to stress loading, creep, and relaxation of the conductor material, it introduces the new problem of providing added clearances to accommodate the increased copper movement from cold to hot conditions and always keeps the winding centrally positioned with respect to the rotor body. Inner-cooled rotors with these construction features are now being built with the full expectation that the inherent causes of rotor-winding distortion will be essentially eliminated from generators of any rating and speed now contemplated by the manufacturer and user.

Mr. J. T. Wilkins: It is now possible to calculate the stress at all points in a rotor winding, provided that the values of the coefficients of friction and the temperature distribution in the winding are known. However, certain data are still lacking regarding the correct value for μ. The estimated values for μ_{w1} and μ_t have varied between 0·3 and 0·12 in papers published since 1936. None of these estimates can be considered reliable for all machines, and there is almost certainly a variation in the coefficients with the condition and type of insulation in the rotor. In smaller machines the stress in the windings depends entirely on the value of μ, and in order to know the limiting size of machine above which precautions against copper deformation must be taken it is necessary to know its value with some accuracy. There is room here for further experimental work.

The other point about which some doubt exists is the temperature distribution in the winding. This aspect does, however, lend itself to reasonably accurate calculation, and several papers on the subject have been published.*†‡ Rotors have been manufactured with varying copper sections down the depth of the slot with a view to achieving uniform temperature throughout the stack. This method of construction enables a finer grading to be obtained than would be feasible by dividing up the winding into separate sections, and it avoids the attendant complications of extra slip-rings, etc.

In calculating the locked-portion stresses in the worked examples the author takes into account only stresses due to thermal effects. Axial compressive stresses are also produced mechanically and may assume fair proportions, as was recently pointed out by Gilson and Taylor.§ This additional mechanical stress may be estimated as follows. If σ_c is Poisson's ratio for copper and σ_s that for steel, an additional axial stress of $\sigma_c f$ is produced by the radial compression stress f in the copper owing to its own centrifugal load, and another superimposed stress of

$$\left[K \times \frac{E_c}{E_s} \times \sigma_s \times \text{mean of } (f_t + f_r)\right]$$

is produced by axial contraction of the iron under its own tangential and radial tensile stresses f_t and f_r. In the above expression K is an empirical constant and is approximately 0·5. E_c and E_s are Young's modulus for copper and steel respectively.

Using these relationships for the example calculated in the paper, it may be estimated that an additional stress of 3 800 lb/in^2 is induced in turn No. 1, and 2 580 lb/in^2 is induced in turn No. 10. Although this is a relatively small increase it is seen from Fig. 4 that it has a marked effect on creep rate.

Dr. D. B. Reay (*in reply*): In reply to Mr. Gilson I would make it clear that I know of no failures through distortion of c.w.s.b. copper windings.

It is appreciated that, with rotor windings of aluminium alloy instead of copper, the increase in the safe limit of rotor diameter is well in excess of the increase in diameter for a given capacity.

Mr. Gilson's comments on preheating, and its detailed treatment in the recent paper by him and Mr. H. D. Taylor,§ are very interesting and illustrate the differences in approach still current among designers to certain aspects of rotor-winding conductor and insulation problems.

Mr. Gilson points out the existence of rotational strains which result in stresses additional to the temperature stress in the portions of a winding locked relatively to the slot wedge. These, however, are not the only strains: with a reasonable maximum net stress in the hottest turn, and stresses near this level in the other turns as in modern practice, about half the contraction effect of the rotational body strain on the mid-length portion of the slot wedge as estimated in Messrs. Gilson and Taylor's paper is offset by the extension strain in this region of the slot wedge and body due to the axial thrusts of the winding. This effect, which is specifically left out of account in my analysis, is on the basis of uniform distribution of thrust across the body section, whereas the local extension strain in the wedge and tooth tip is likely to be higher than the overall average. There are other, minor, strains, and so far as the net strain in the mid-length portion of the slot

* Soderberg, C. R.: "Steady Flow of Heat in Large Turbine Generators," *Transactions of the American I.E.E.*, 1931, p. 782.

† Peck, G. E.: "Heat Flow in Turbine Generator Rotors," *ibid.*, 1934, p. 1359.

‡ Fechheimer, C. J., and Penney, G. W.: "Ventilation of Turbo Alternators—Concluding Study," *ibid.*, 1926, p. 253.

§ Gilson, W. J., and Taylor, H. D.: "Field Preheating for Large Turbine Generators," *Transactions of the American I.E.E.*, 1954, 73, Part IIIB, p. 1375.

wedge is calculable it appears to be small; it can, I suggest, safely be left out of account in a computation which can hardly be more than comparative. On the other hand, I agree that, if the cooling system is such that turns in the upper portion of the stack are in the high-temperature region, the centrifugal strains in these turns should be included in e_1, e_2, etc.

The important factor of wear and tear of slot-turn insulation is clearly related to frequency of starting; but, as between weekly and daily operating cycles, there is, I believe, a negligible difference in rate of deformation of c.w.s.b. copper windings.

As regards Mr. Horsley's first query, I do not think the occurrence of severe deformation in windings of ordinary copper only after relegation to 2-shift working is inconsistent with creep action alone. The high relaxation rate of ordinary copper following starting up results in a much reduced creep rate and therefore in a relatively low average rate measured over a long on-load period. With frequent starting and renewal of full stress the average creep rate would correspondingly increase.

In the determination of μ in a discarded winding the argument is based on observations of increased hardness, not of deformation.

I would not expect the rate of deformation with brass wedges to be different from that with steel wedges except in so far as the tensile strain in the wedge and tooth will be greater in the former case. Nor do I see why sectionalized wedges should, apart from ease of withdrawal, be preferred to full-length ones, since the average rate of accretion of frictional restraint is the same in each case. The desired reduction in the resistance offered by the slot wedge to the expansion of the winding might be achieved by providing, throughout the length of the wedge, a series of fine, suitably-pitched transverse saw cuts extending from the underface of the wedge to within a short distance of its outer bearing face.

Mr. Horsley's suggestion that creep rates in copper under tension may be much lower than the rates under compression supports the case for further work on compression creep rates.

I agree that in the case considered in the paper the calculated stresses in the turns are not much affected by taking the top turn as reference instead of the slot wedge; but the difference would be much greater with the small temperature-gradients of modern practice.

The adjustment to initial creep rate on account of the operating strain being in the opposite sense to the cold-work strain was in fact applied in the way Mr. Horsley suggests.

That the degree of relaxation over, say, 130 hours is too small to affect the creep rate substantially in an on-load period of that length by no means implies that the creep strain over much longer periods is negligible.

Regarding Mr. Horsley's suggestion that the estimates of deformation in the paper should have been applied to soft-copper windings for comparison with observed deformations, I would point out that the results would have been vitiated by the necessity for assuming turn temperatures.

Messrs. Laffoon and Baudry have sought a solution to the problem of rotor-winding deformation mainly through a low value of μ_{w1} and zero temperature gradient down the stack. The extension of sliding throughout the slot-wedge/top-turn interface in large rotors is a noteworthy achievement. Incidentally, it emphasizes the diversity of view still evident in regard to the design of end-turn packings, for a low μ_{w1} means that allowance must be made for considerable movement of the end turns.

Several contributors view the rotor winding as expendable. This approach has the powerful attraction of minimum initial cost, with the possibility, at this stage of experience, that this is also the final cost. Something depends, however, on the availability of facilities for prompt rewinding, in view of the heavy capital charges on idle plant.

I must correct Mr. Kilner's suggestion that the rotor-winding failures to which he refers were due to loading beyond rated capacities. The machines operated at remarkably high load factors, and, therefore, for long periods daily carried sustained loads near the designed output; but the maximum temperatures of the rotor windings, which were carefully recorded, varied between 96°C and 125°C, depending on the load. These figures are (to quote the contract specifications) within the "observed maximum safe temperature for continuous running of 130°C." At no time have these rotors been loaded to the maximum output of the exciters.

The large variations in deformation between the upper and the lower turns of the windings which failed indicate that the critical factor in these earlier (soft-copper) windings was the temperature gradient down the stack, rather than average temperature level.

No failures have occurred in the four rotors referred to by Mr. Kilner as wound with hard-drawn tough-pitch copper. The commissioning dates of these machines are:

Machine serial No.	Date
73773	October, 1939.
73774	July, 1940.
79253	January, 1945.
79254	April, 1945.

Since the publication of the paper one of these rotors (No. 73774) has been examined, both end-bells being removed for the purpose. The contraction of the windings was so small as to be of negligible effect. A semi-flexible system of end packings is employed, and the rotor design and the operating conditions are similar to those for other rotors, wound with soft copper, in which failures have occurred.

It seems clear that, for the conditions applying to the rotors referred to above, 10% cold working of tough-pitch copper confers an effective and permanent advantage over the annealed state. This is a more favourable conclusion than I had previously felt—in the absence of direct evidence—to be justified.

Without dismantling the winding of rotor No. 73774 it was of course impossible to determine the remanent hardness of the turns, but from the observations recorded in Section 2.2.4 it can be concluded that the rotor winding has undergone no super-elastic strain, such deformation as has occurred being due to creep strain.

It is unlikely that the early winding referred to in Section 2.2.4 as having undergone severe deformation was assembled in the hard-drawn condition as later understood (i.e. corresponding to 10% reduction), but it was evidently somewhat harder than in normal practice.

Dr. Benson's confirmation of several points in my interpretation of the results of Messrs. Benson, McKeown and Mends's investigations is very welcome. I agree that the long-term extrapolations from test results employed in Fig. 4 are open to question, and this point was discussed in Section 10.

I agree with Mr. Wilkins on the importance of the determination of μ for appropriate types of slot-winding insulation under various conditions. Other contributors have indicated that much progress has been made in this direction.

As implied by my reply to Mr. Gilson, I think Mr. Wilkins has overestimated the corrections to be made to my figures of turn stress to take account of strains other than direct temperature strains.

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, FEBRUARY 1956

CONTENTS

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